Analog Optical Signal Processing Based on Optical Waveform Synthesis

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Concept

- With respect to the electric field, a photodiode provides multiplication and integration

$$I = \int \left| E(t) \right|^2 dt$$

- Easily used to construct a field correlator

$$I(\tau) = \int \left| E_1(t+\tau) + E_2(t) \right|^2 dt = \int E_1(t+\tau) E_2^*(t) dt + c.c. + const.$$

- Why not use for signal processing?

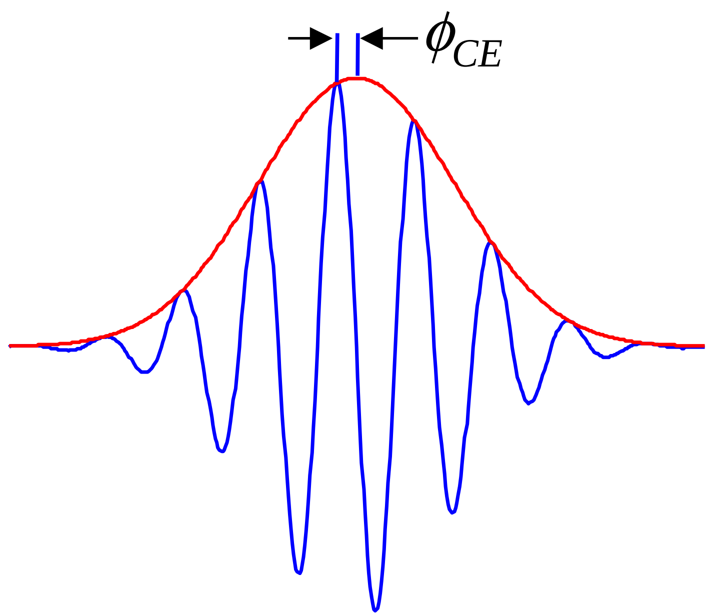
PHASE

$$E(t) = \hat{E}(t) e^{i(\omega t + \boxed{\phi})}$$

- Address using recent advances in carrier-envelope phase control

Carrier-Envelope Phase

- Generally in optics:
  - absolute phase never matters
  - only relative phases
- Ultrashort pulse (~10 fs or less)
  - envelope provides “absolute” phase reference

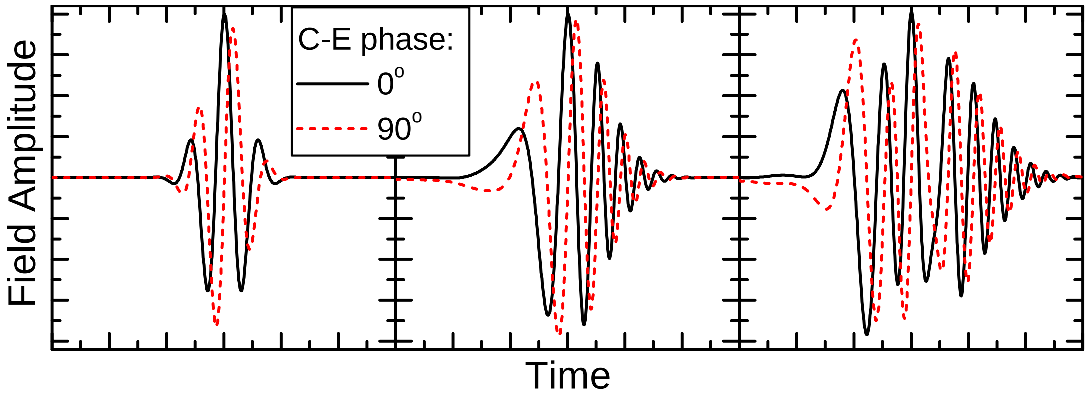


Of course, the phase of the envelope is referenced to a clock and not “absolute”

Outline

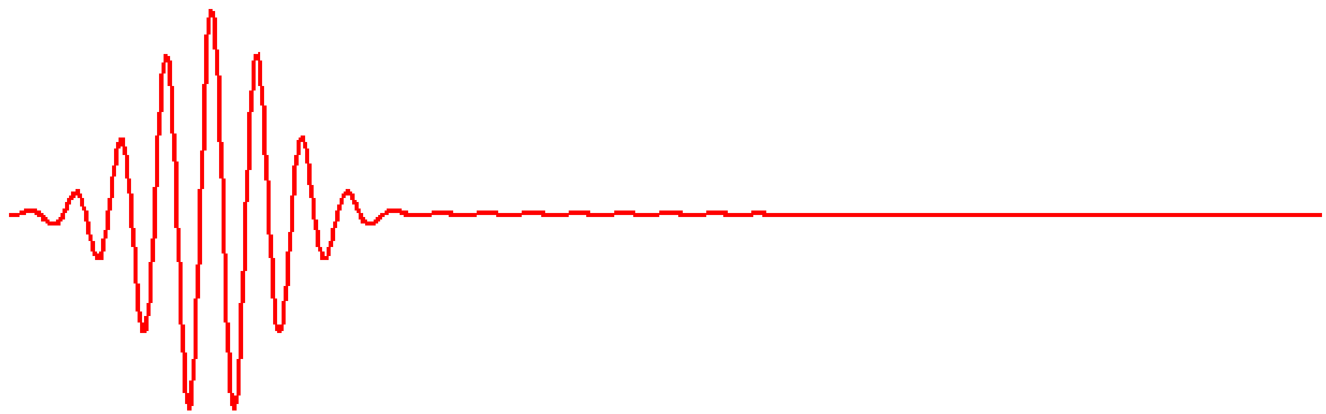
- ➢ Carrier-envelope (ϕ_{CE}) phase in waveform synthesis
- ➢ Technique for stabilizing ϕ_{CE} from modelocked lasers
    - Uses frequency domain methods
- ➢ Results for ϕ_{CE} coherence
- ➢ Discuss possible means of measuring "absolute" ϕ_{CE}
- ➢ Prototype correlator

ϕ_{CE}, waveforms and correlations



Delay

Group vs. Phase Velocity

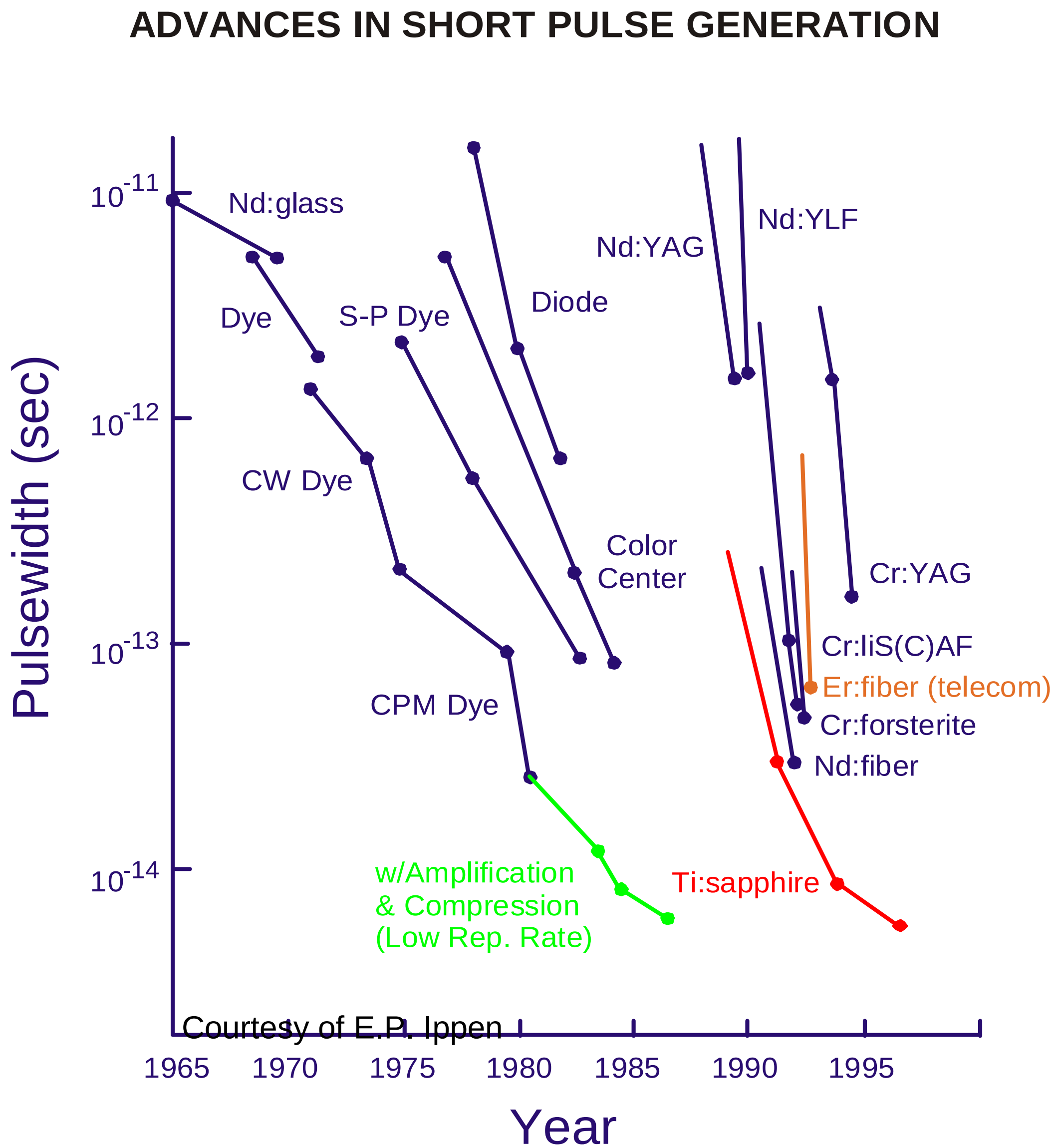


- Carrier-envelope phase is dynamic:
  - In any material, the group and phase velocities differ
  - Therefore carrier phase slowly drifts through the envelope as a pulse propagates

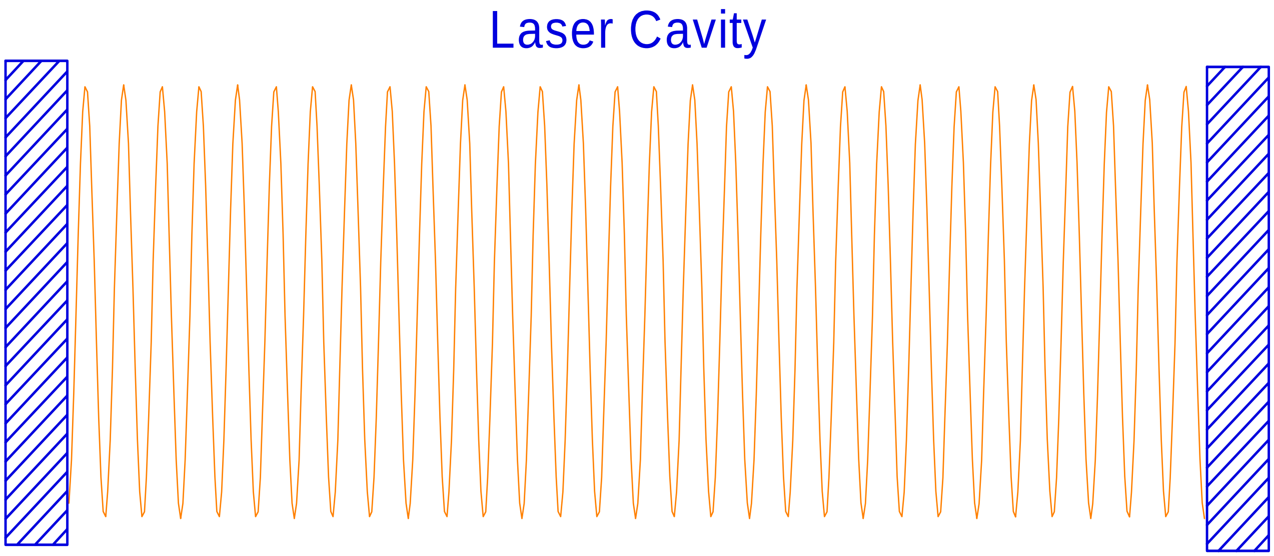
Historical Progress in Ultrashort Pulses

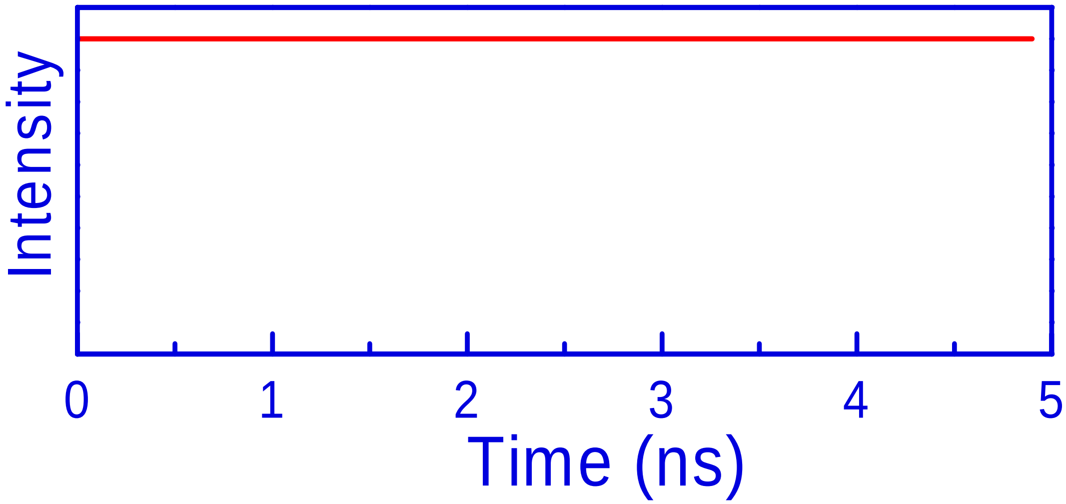
< 10 fs directly from oscillator

- high repetition rate



Modelocking





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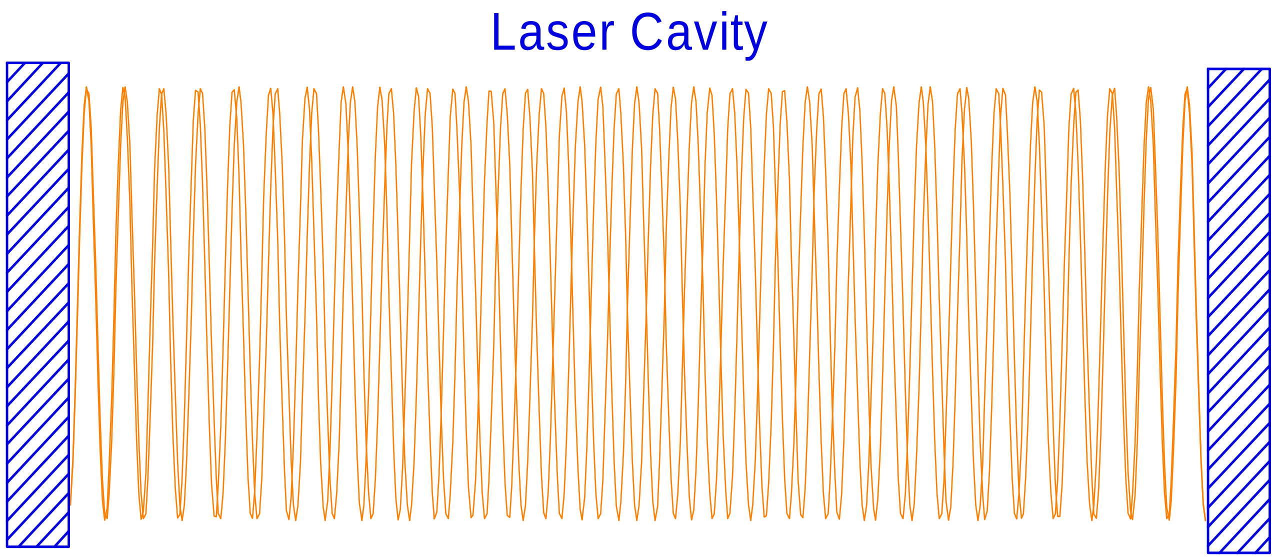
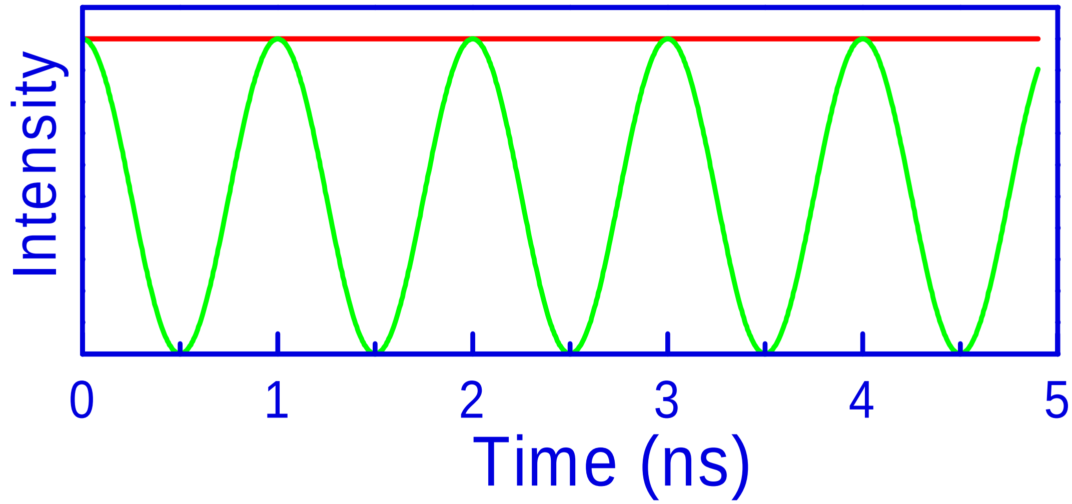
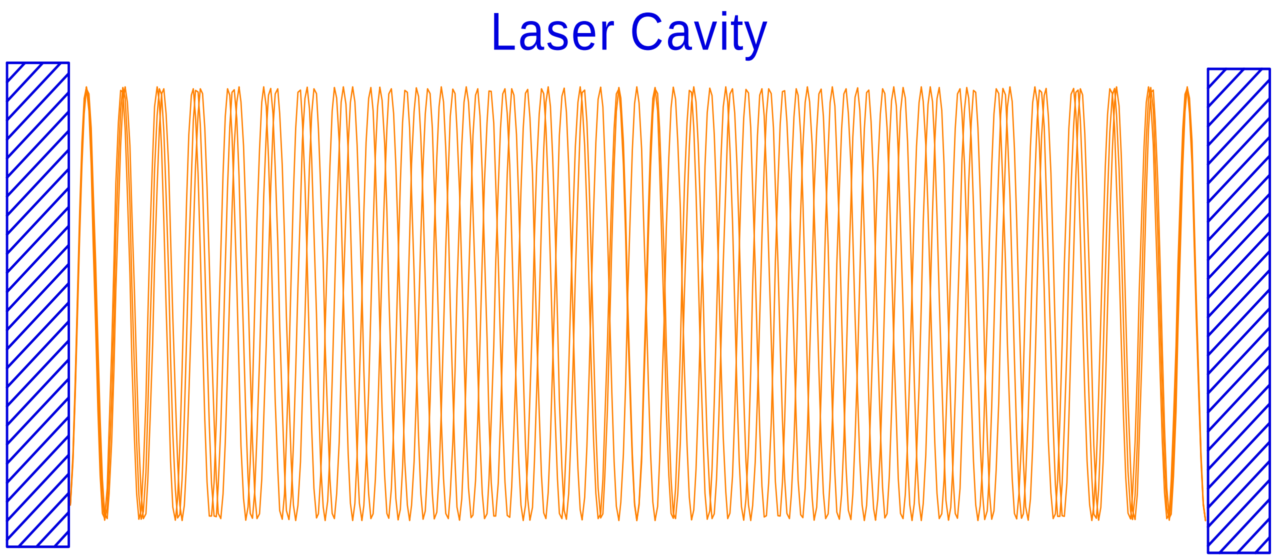
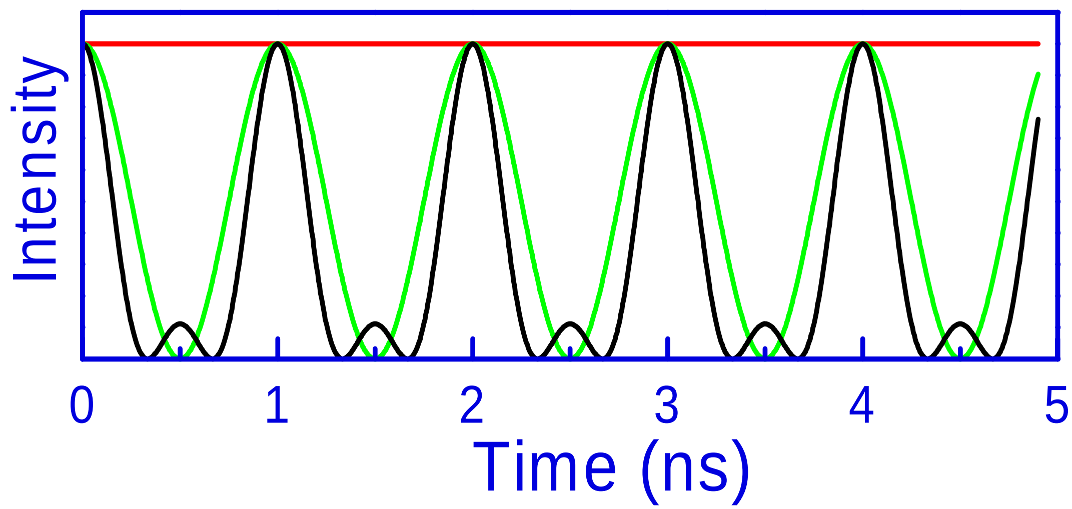
Modelocking





Modelocking





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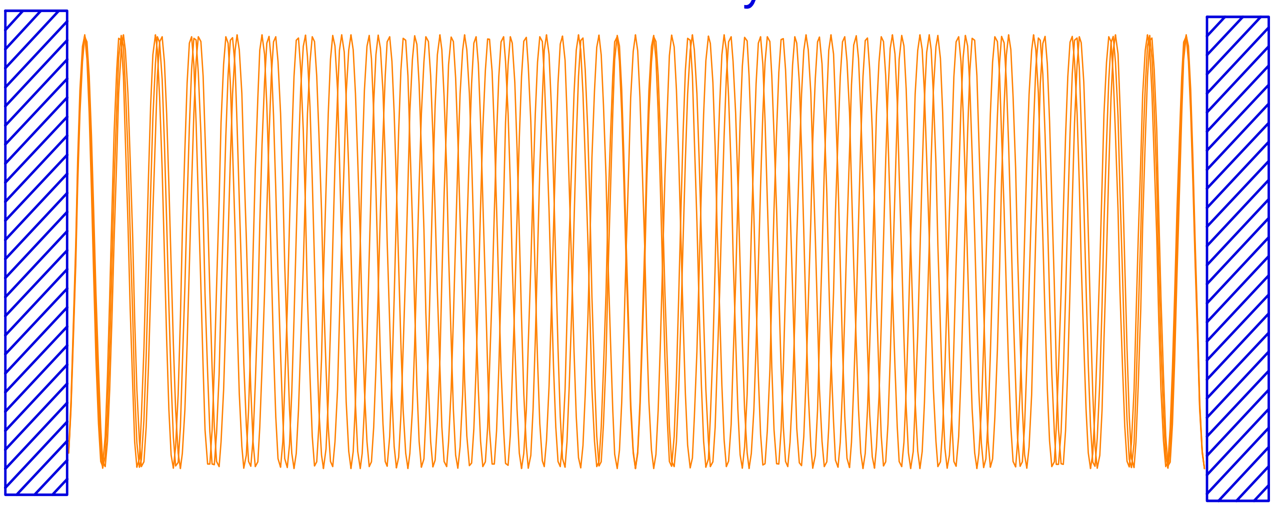
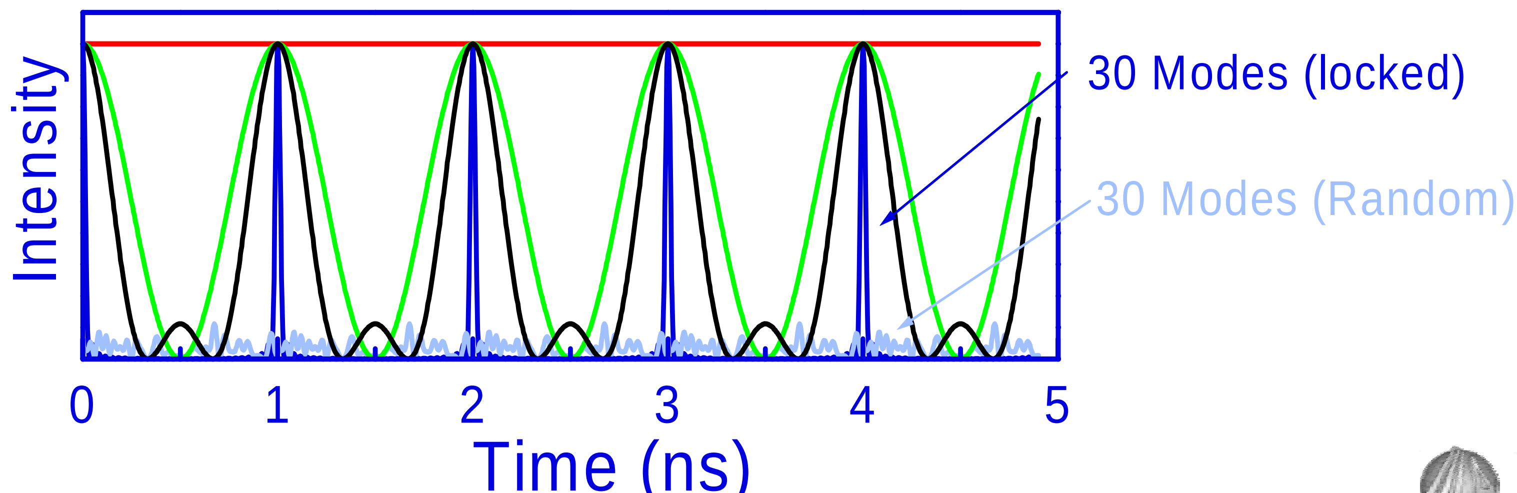
Modelocking

Laser Cavity

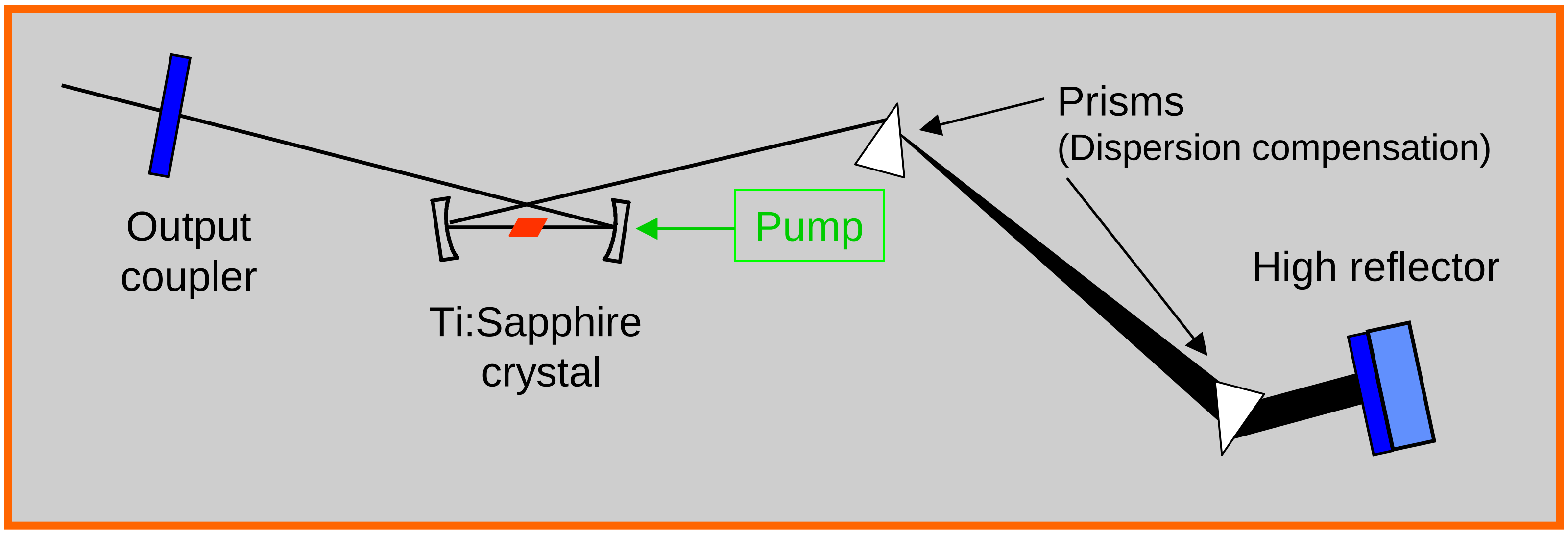


- Constructive interference between phase locked cavity modes



Kerr Lens Modelocked Ti:sapphire

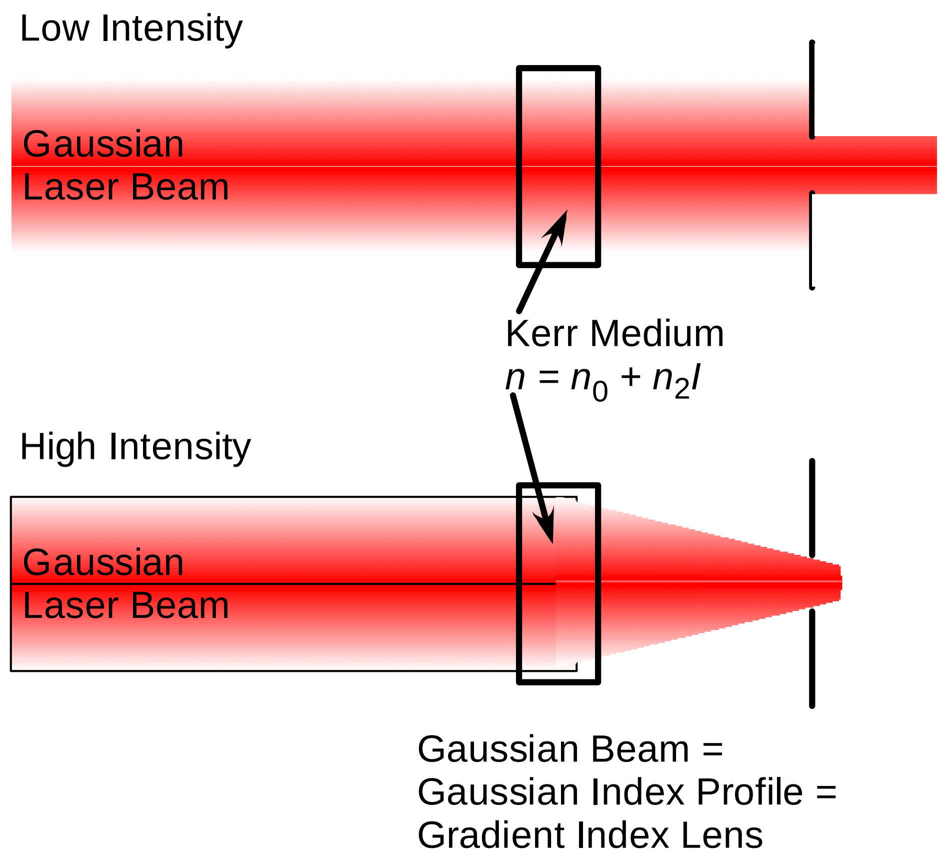
- Ti:sapphire has large bandwidth
- Supports shortest pulses
- Simple (amazingly)
- Modeled as dispersion managed soliton



M.T. Asaki, et al, Opt. Lett. 18, 977 (1993)

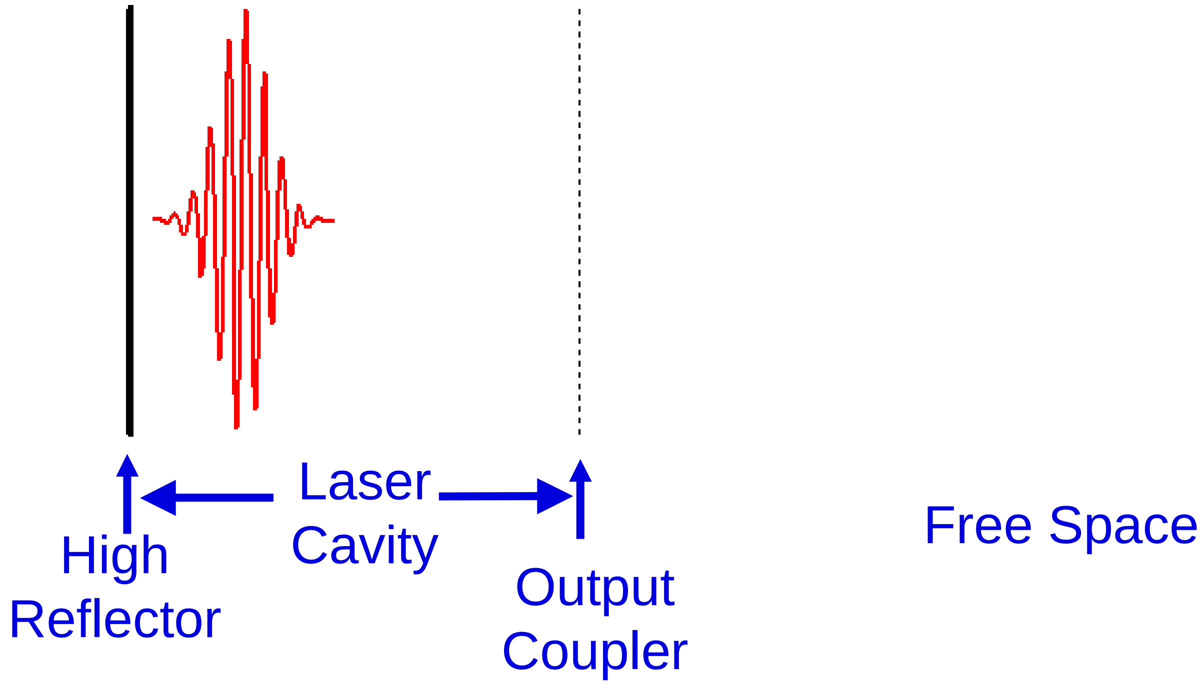
Kerr Lens Modelocking

- Kerr Lens & Aperture gives increased transmission at high intensity
- Increased transmission at high intensity = saturable absorption
- Short, intense pulse preferred in laser
- Kerr effect instantaneous
- Not self starting



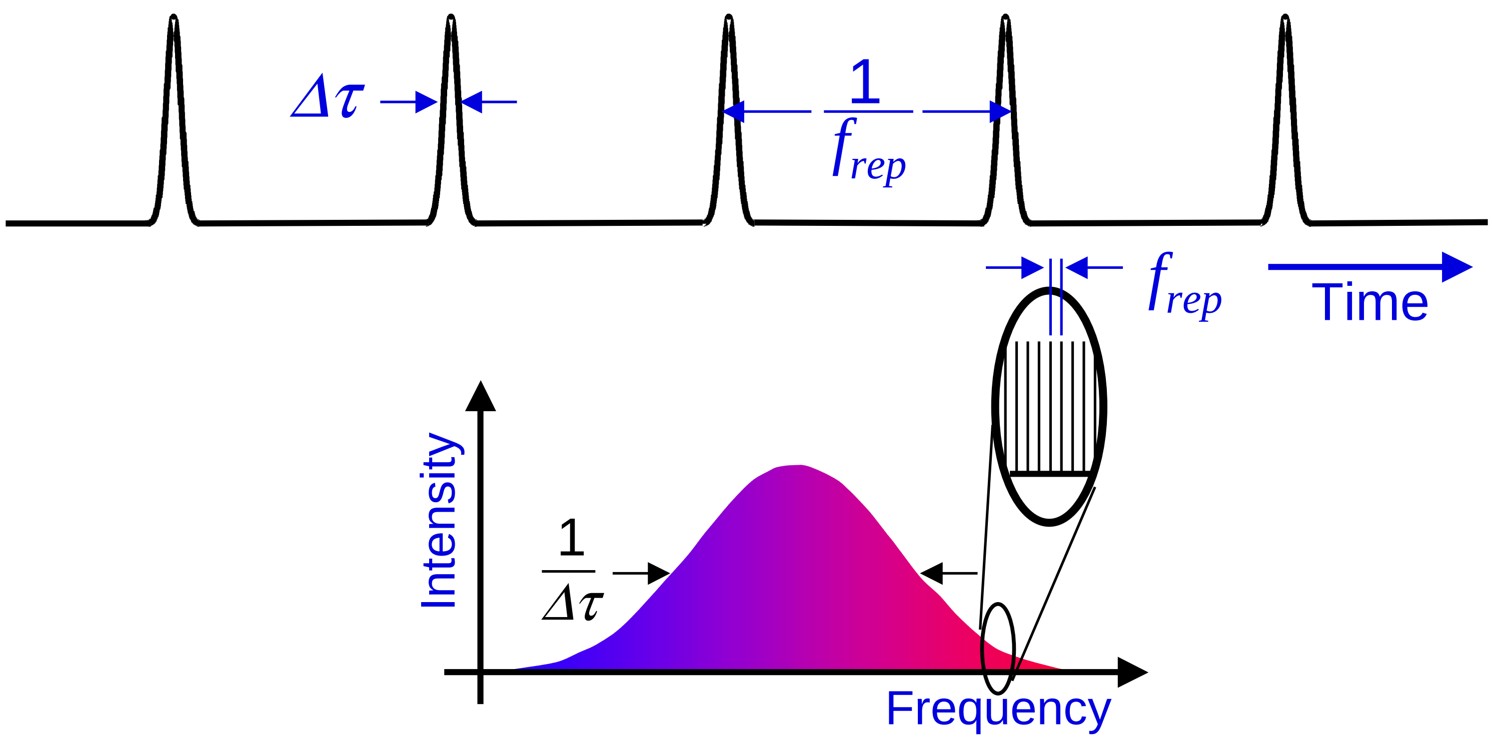
Group vs. Phase in Modelocked Lasers

- Each pulse emitted by a modelocked laser has a distinct envelope-carrier phase
  - due to group-phase velocity differential inside cavity



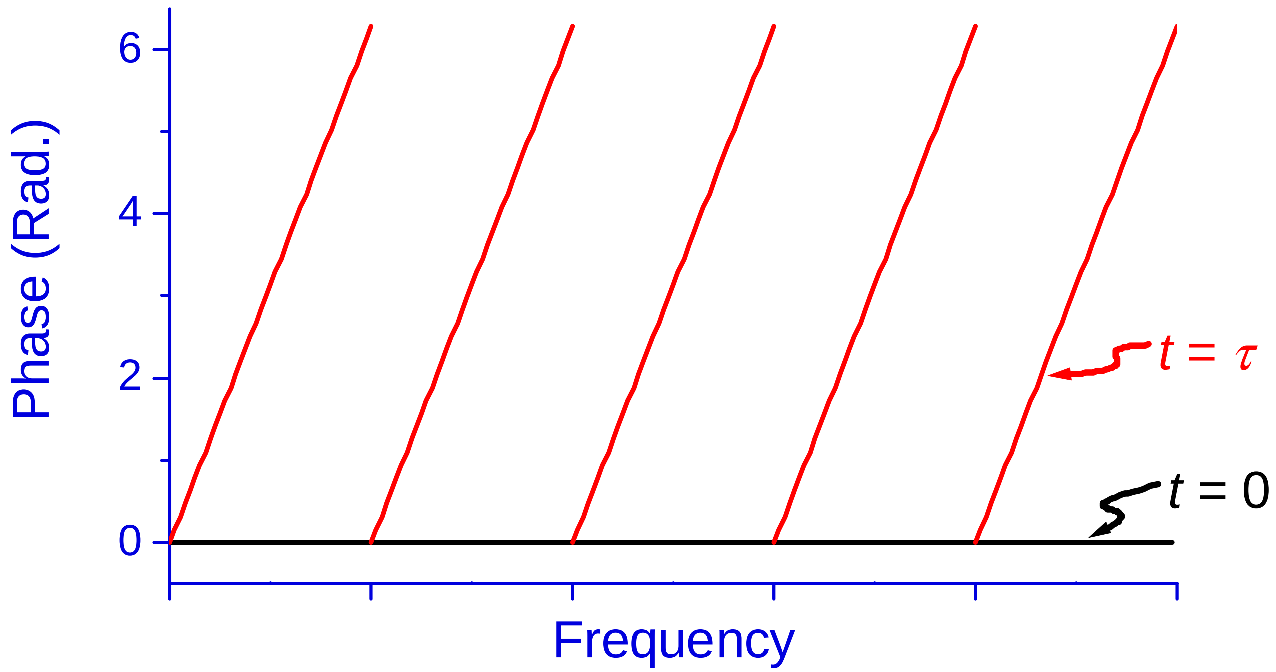
Frequency Spectrum of ML Laser

- Temporal pulse width ↔ frequency width
- Train of pulses ↔ comb of frequencies



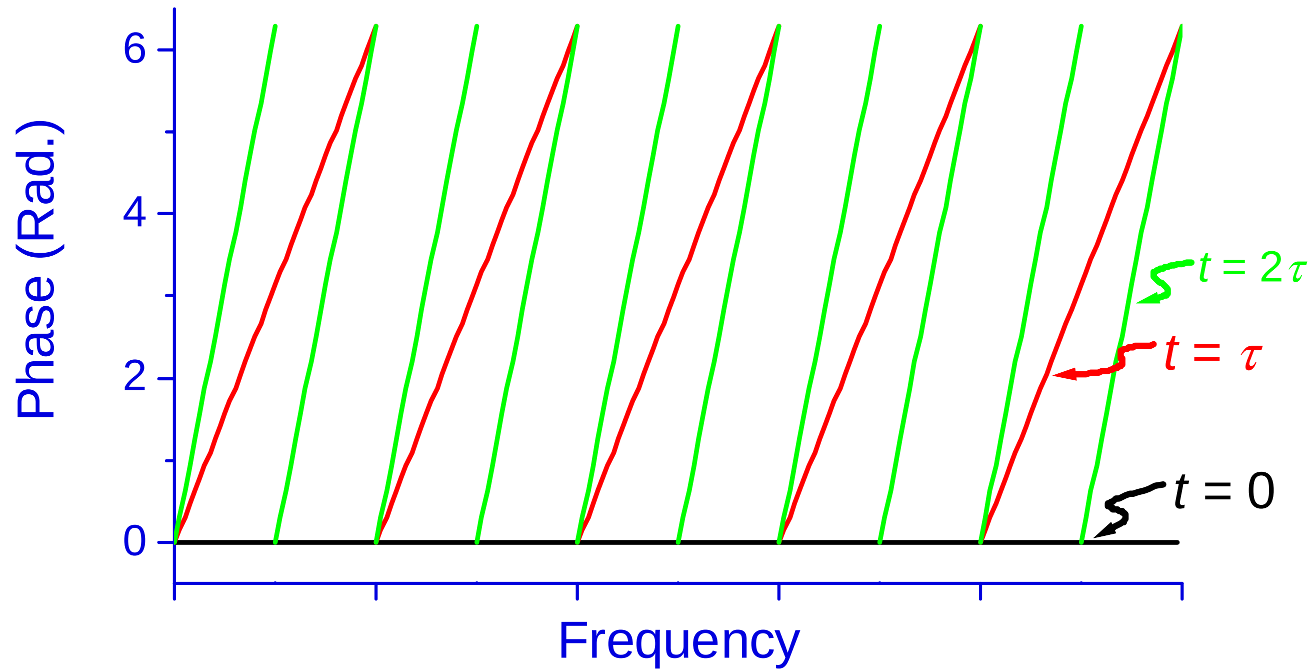
Group vs. Phase in Spectrum

- Shift in time is linear phase with frequency



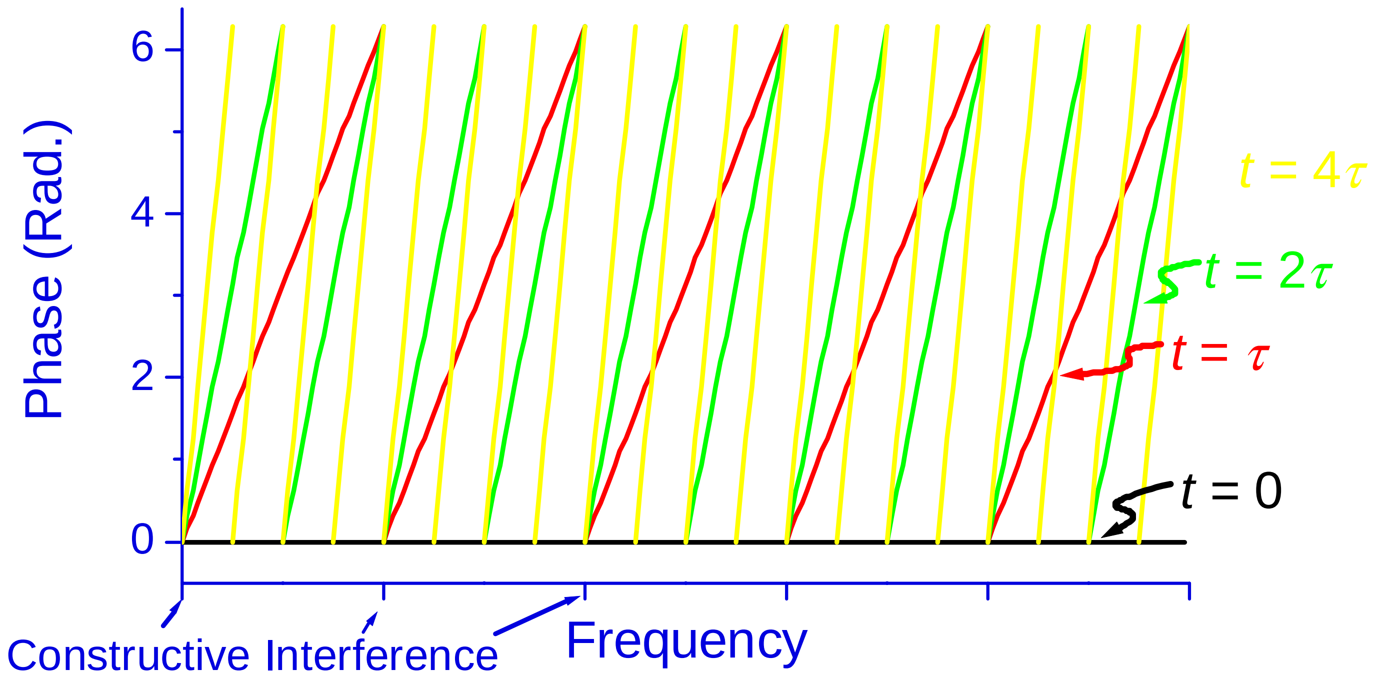
Group vs. Phase in Spectrum

➢ Shift in time is linear phase with frequency



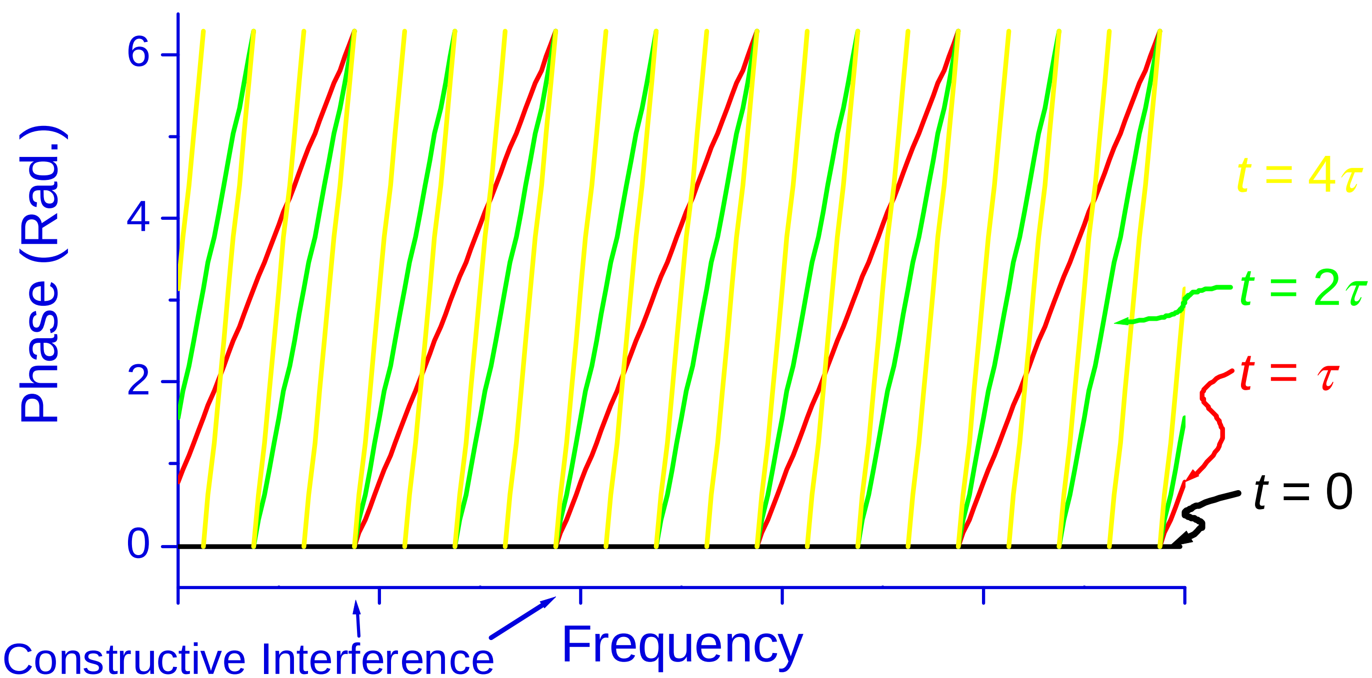
Group vs. Phase in Spectrum

- Shift in time is linear phase with frequency
- Constructive interference results in frequency comb



Group vs. Phase in Spectrum

- Pulse-to-pulse phase shift shifts frequency of constructive interference
- Cavity group-phase velocity difference determines absolute optical frequencies



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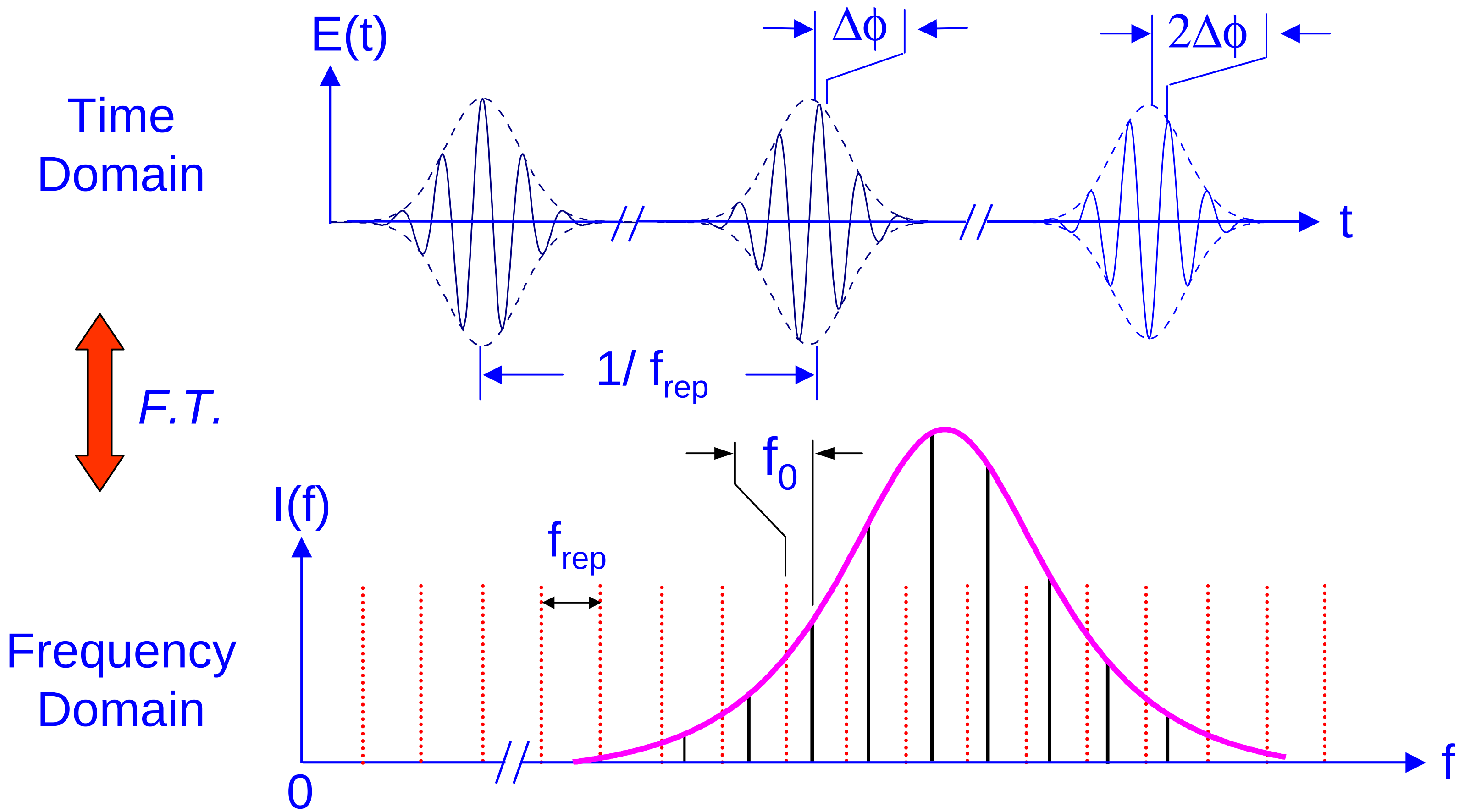
Time Domain ↔ Frequency Domain



- Frequency modes of the fs pulse are offset from $f_{n=0}=0$ by f_0

$$\boxed{2\pi f_0 = \Delta\phi \; f_{rep}}$$

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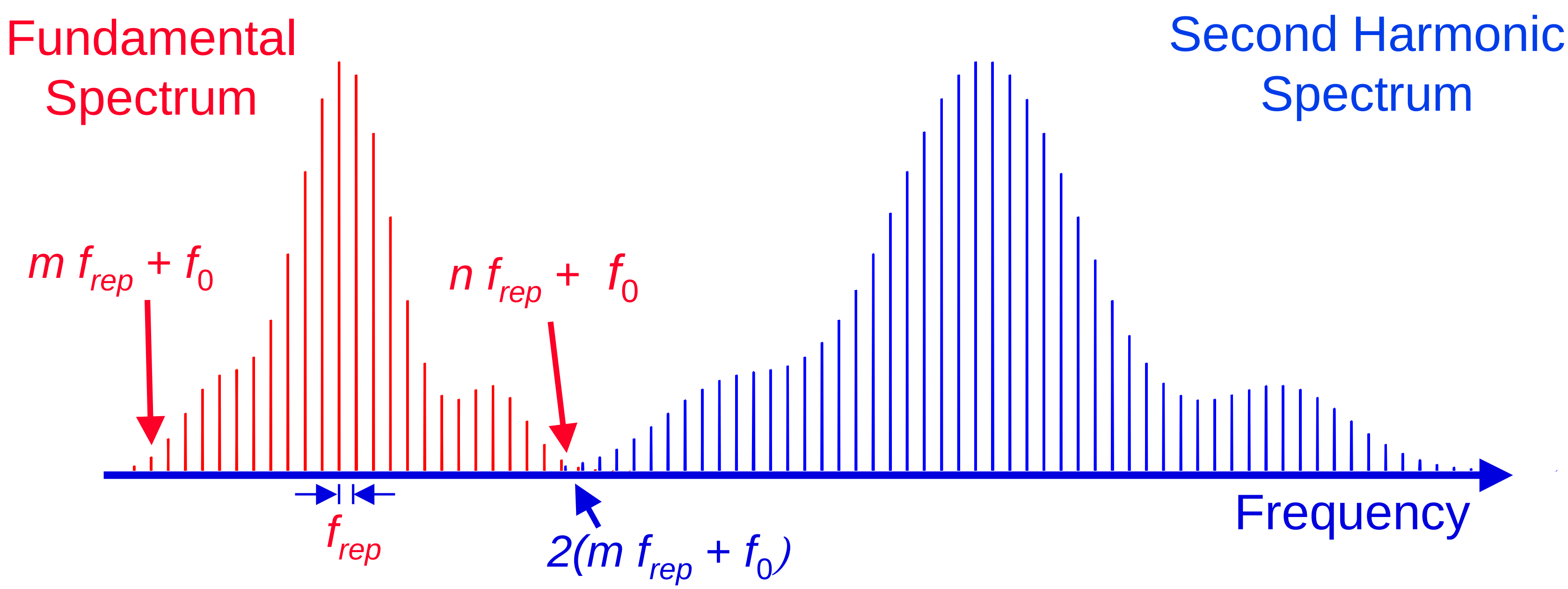
Self Referencing Technique

- How can we control the absolute frequencies, and hence the group-phase velocity difference?
- Self-referencing:

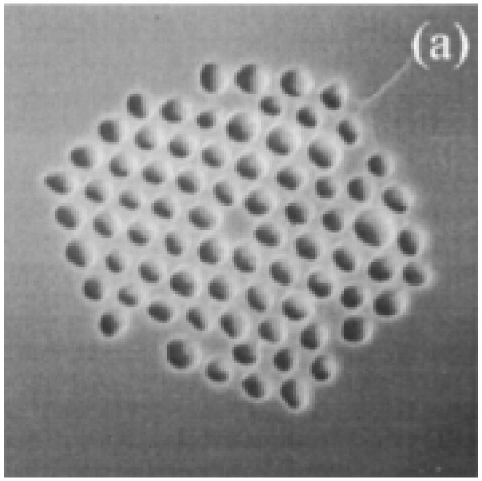


- Beat frequency at overlap = f_0

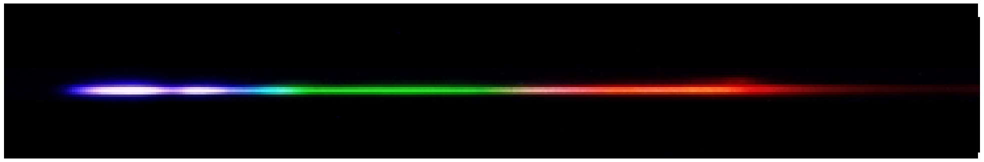
Generation of Bandwidth

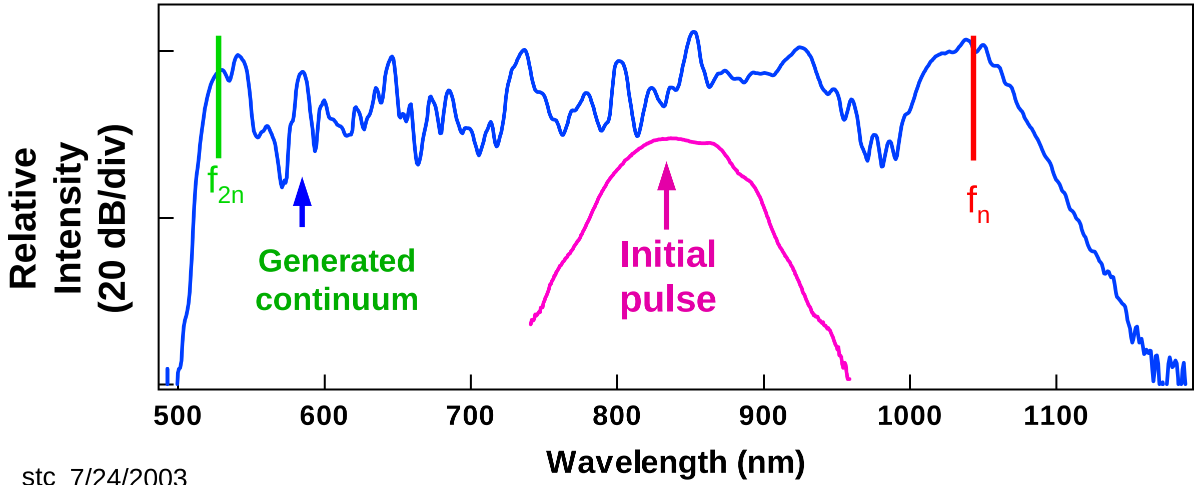
- Microstructured fiber
  - dispersion zero at ~800 nm
  - pulses do not spread
  - continuum generation via self-phase modulation

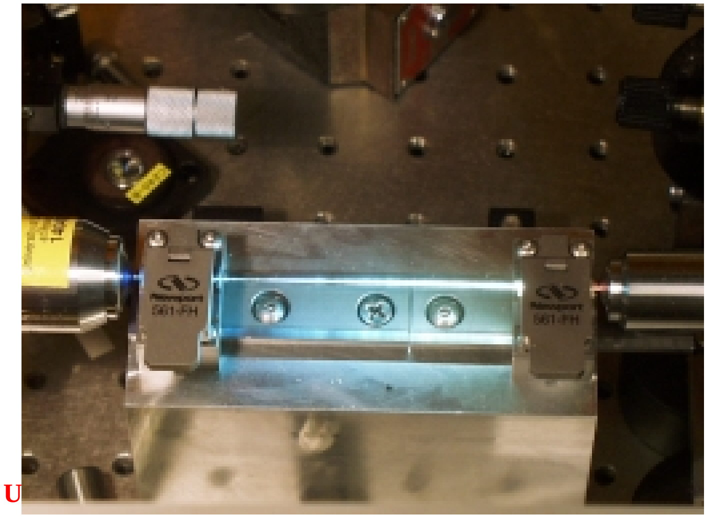
Developed at Bell Labs & Univ. of Bath



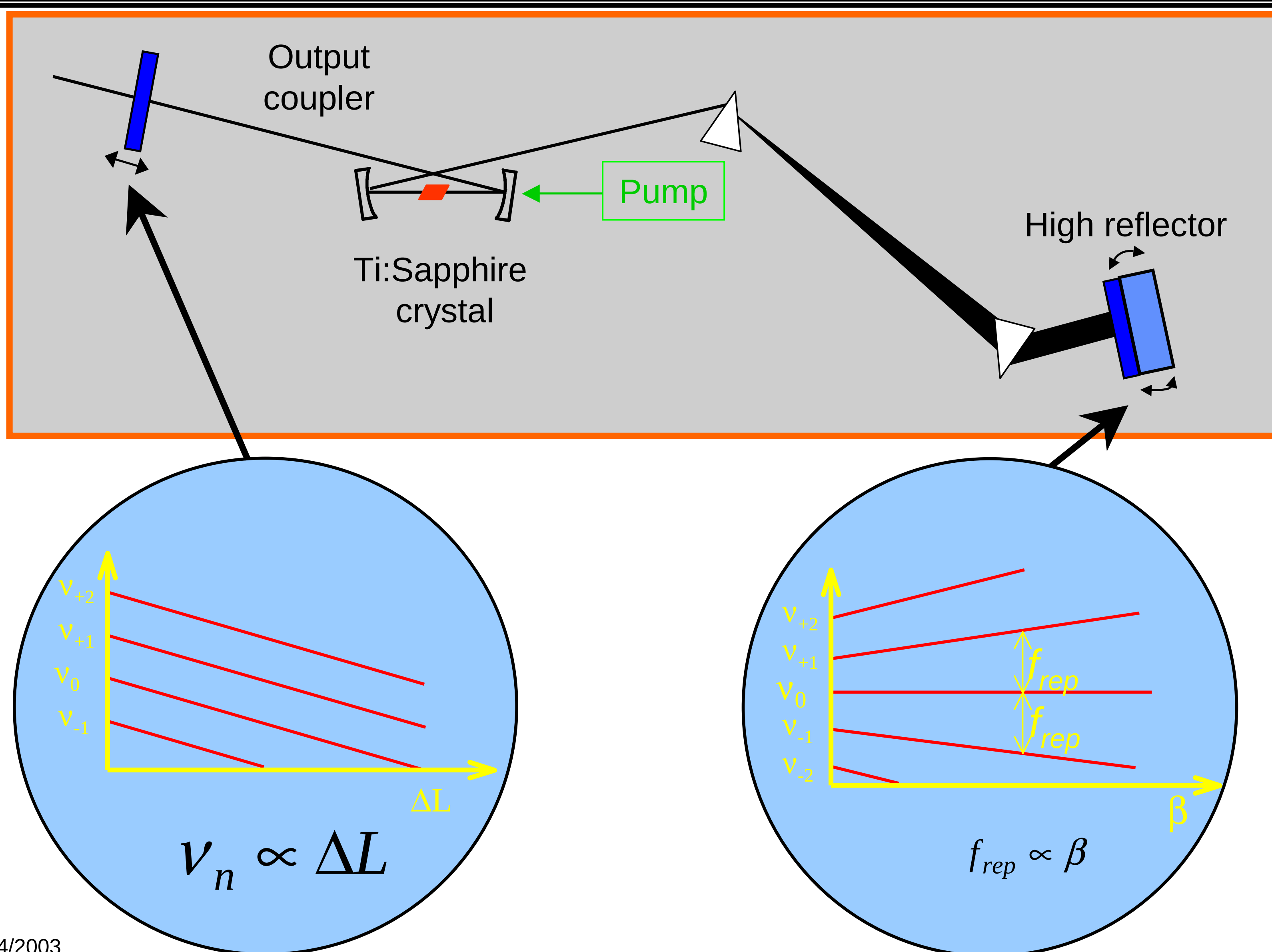
J.K Ranka, et al, Opt. Lett. ***25****, 25 (Jan. 2000)*



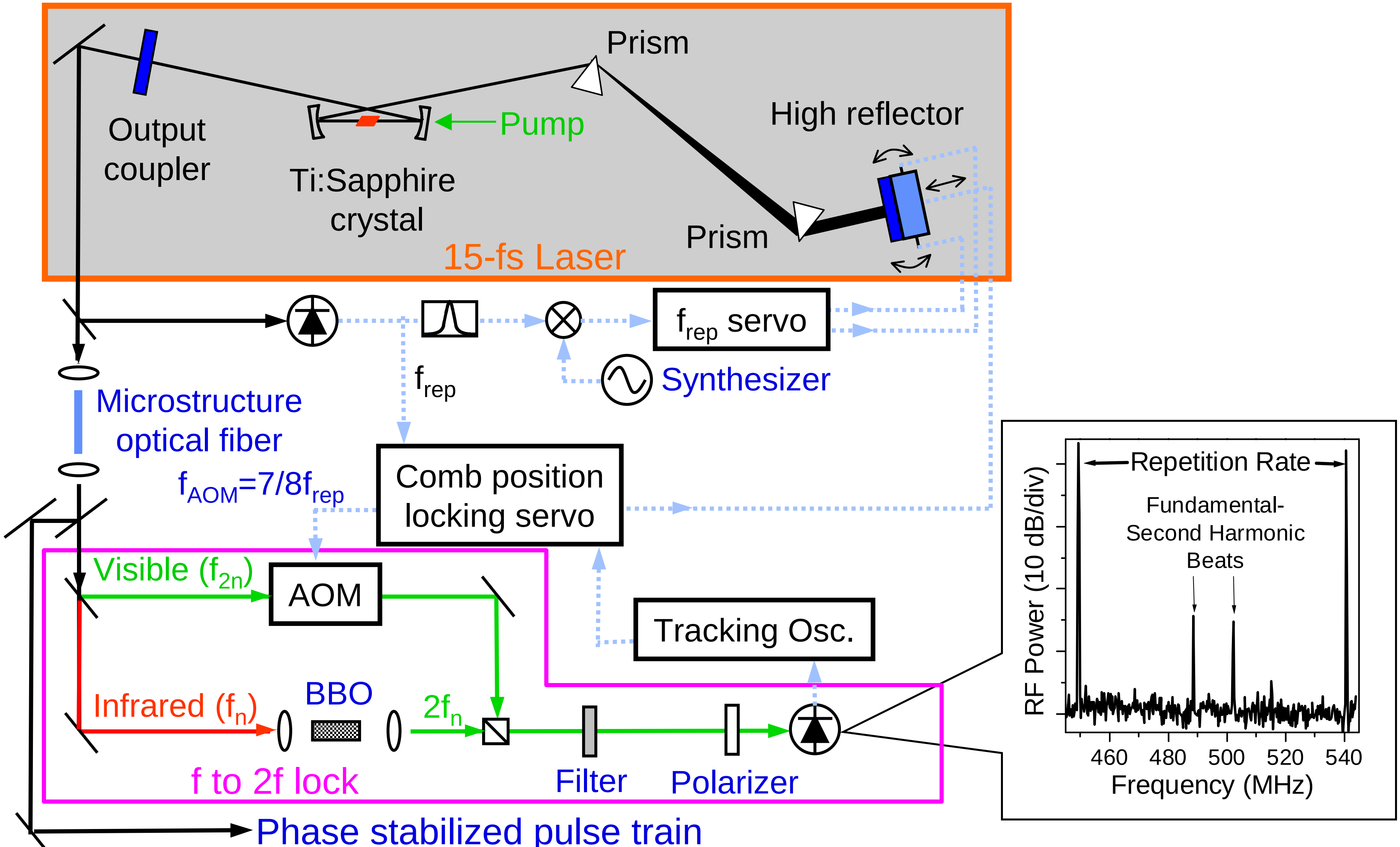




Control of Laser Comb



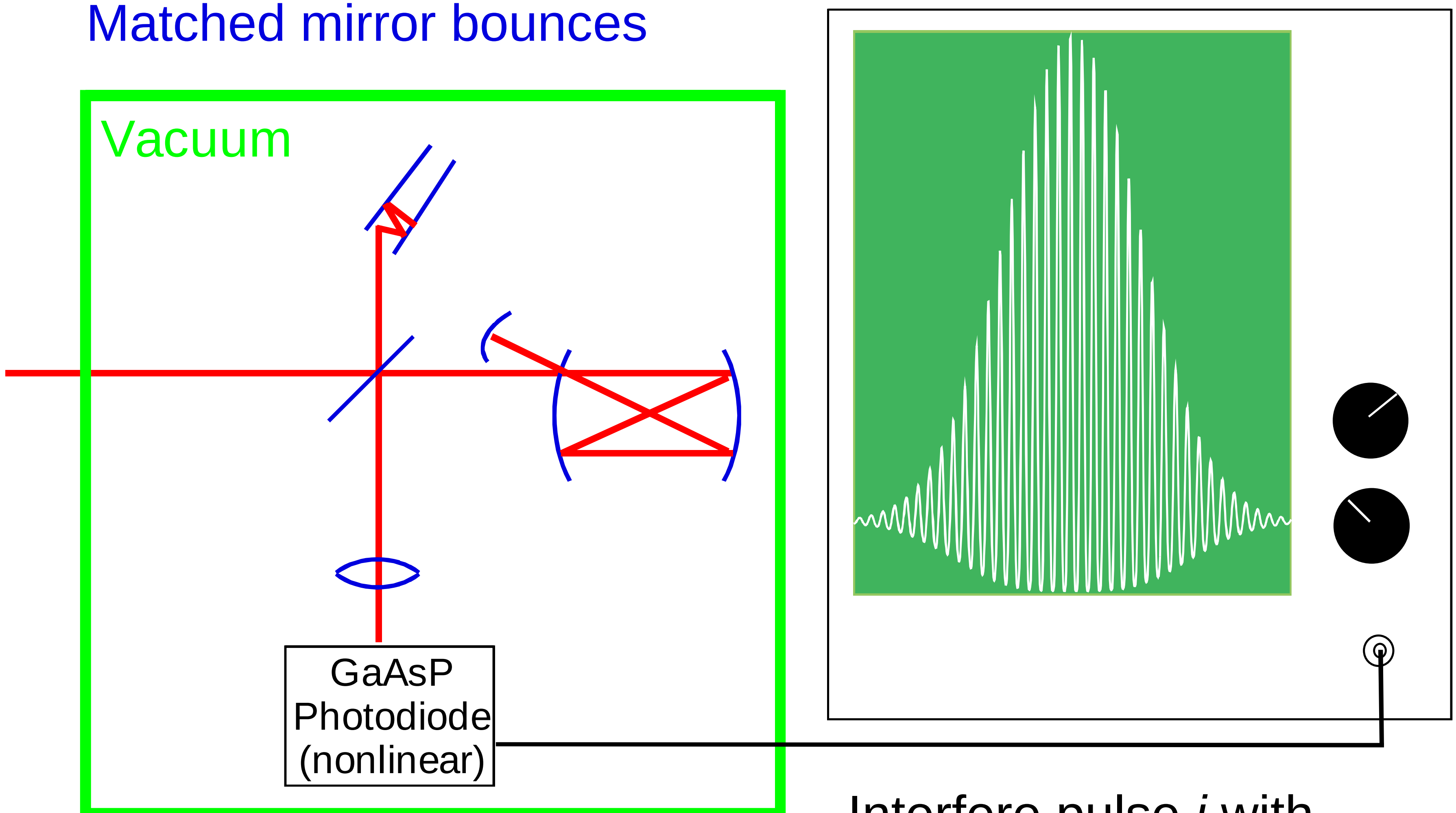
Experiment



Prism
Output coupler
Ti:Sapphire crystal
Pump
High reflector
Prism
15-fs Laser
f_{rep} servo
f_{rep}
Synthesizer
Microstructure optical fiber
f_{AOM}=7/8f_{rep}
Comb position locking servo
Visible (f_{2n})
AOM
Tracking Osc.
Infrared (f_n)
BBO
$2f_n$
f to 2f lock
Filter
Polarizer
Phase stabilized pulse train
Repetition Rate
Fundamental-Second Harmonic Beats
RF Power (10 dB/div)
460
480
500
520
540
Frequency (MHz)

Time Domain Cross-Correlator

Matched mirror bounces

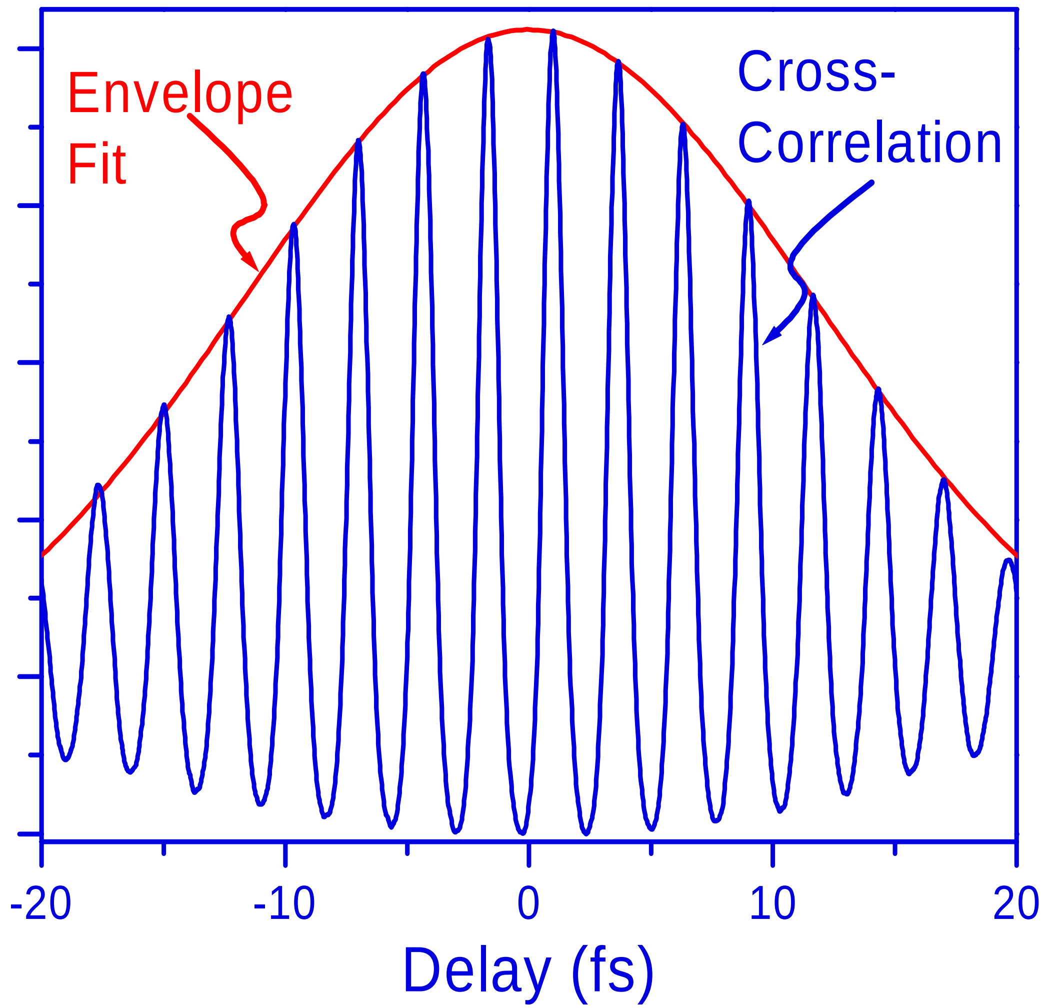


L. Xu, et al., Opt. Lett. 21, 2008 (1996)

Interfere pulse *i* with pulse *i* + 2.

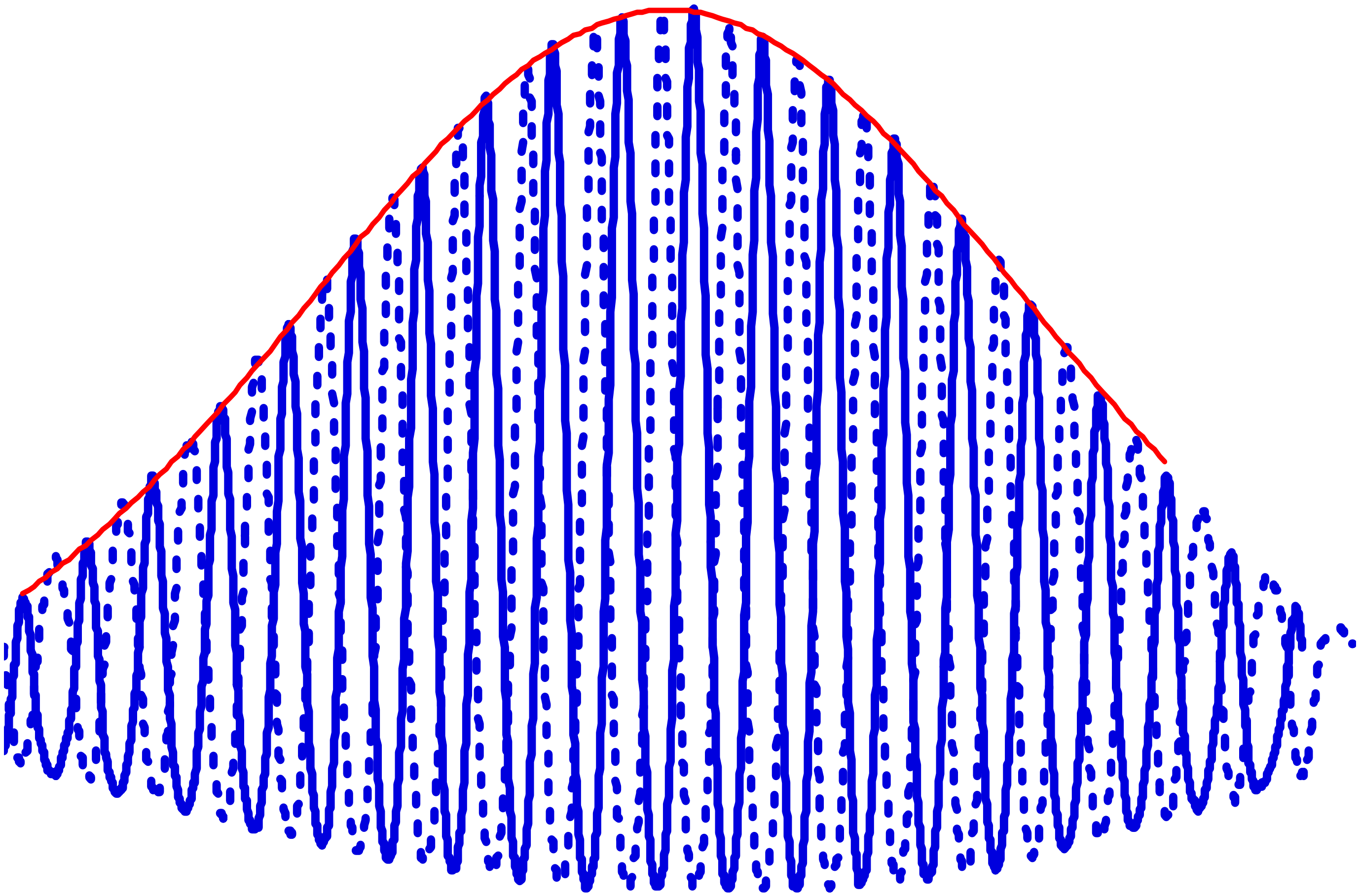
Cross Correlation

- Auto-correlation is always symmetric
- Cross-correlation fringes shift: pulse to pulse phase
- Fit to obtain envelope peak
- Extract carrier phase shift relative to envelope



Phase Stabilization!

- Shift of pulse-to-pulse phase by ~π



Nonlinear Phase in Fiber

- Spectral broadening is highly nonlinear
  - Amplitude noise converted to phase noise
  - Simple estimate (ignoring dispersion)

$$\delta\omega_{max} = 0.86\ \Delta\omega\ \phi_{max} \qquad \text{[Agrawal]}$$

  - Yields ϕ_{noise} approaching 2π

- Measure ϕ_{max} & phase noise interferometrically

*A Poppe, et al, Appl. Phys. B **72** (2001) pp 373-376*

Amplitude to Phase Conversion

Phase noise can limit our ability to perform waveform synthesis: $\Delta\phi_{CE} = 2\pi\delta / f_{rep} + \Delta\phi_{NL}$

Fiber phase noise is contributed by:

$$\phi = \frac{2\pi}{\lambda}\left(n_o + n_2 I(t)\right) l$$

$$I(t) = I_o \left(1 + \frac{\Delta I(t)}{I_o}\right)$$

Nonlinear phase is the intensity-dependent contribution from ϕ:

$$\Delta\phi_{NL} = \frac{2\pi}{\lambda} n_2 \, \Delta I(t) \, l = C_{A-P} \, \Delta I(t)$$

C_{A-P} is the measure of conversion between amplitude to phase noise (rad/mW)

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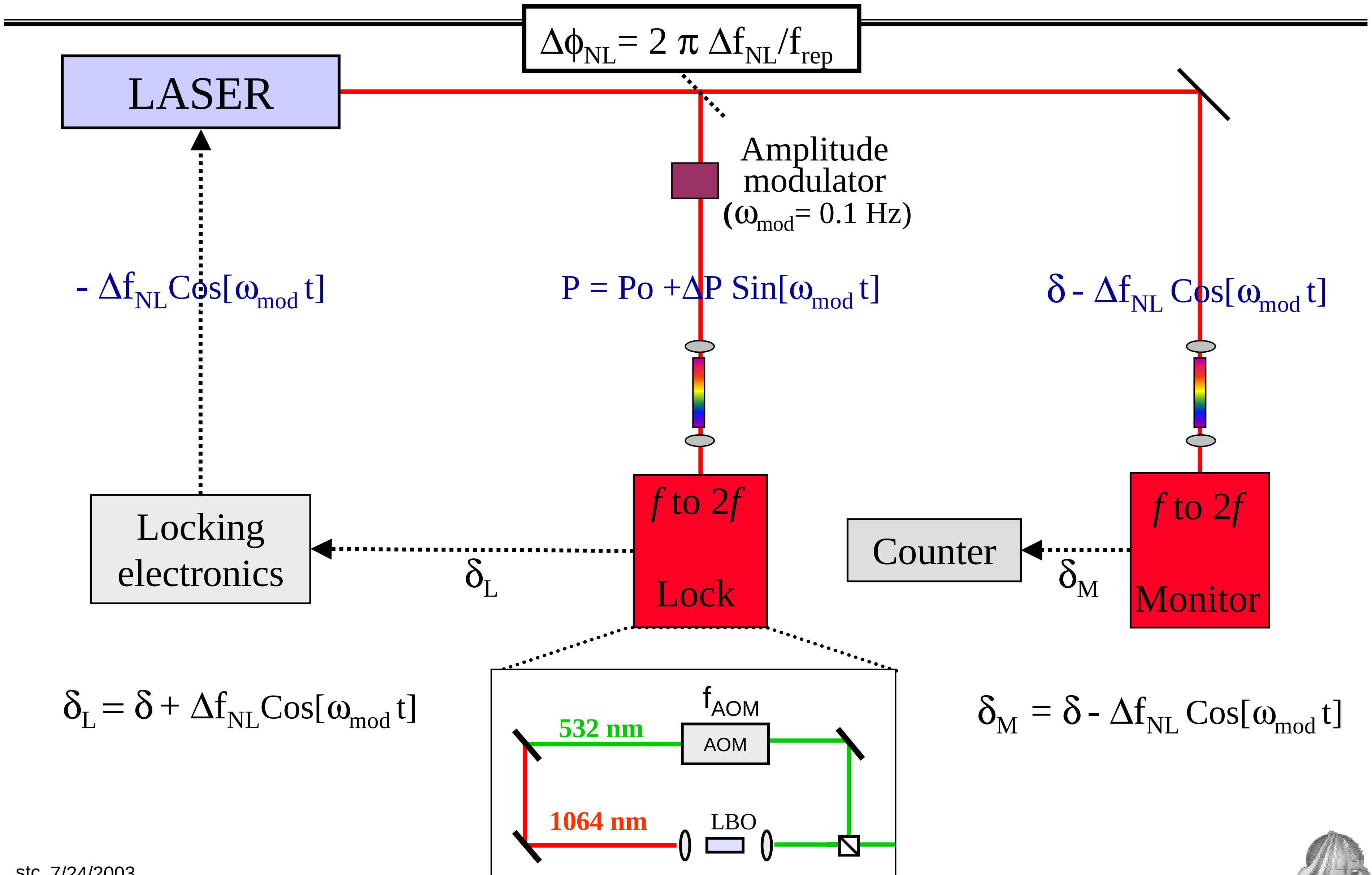
Dueling *f* to 2*f* 's



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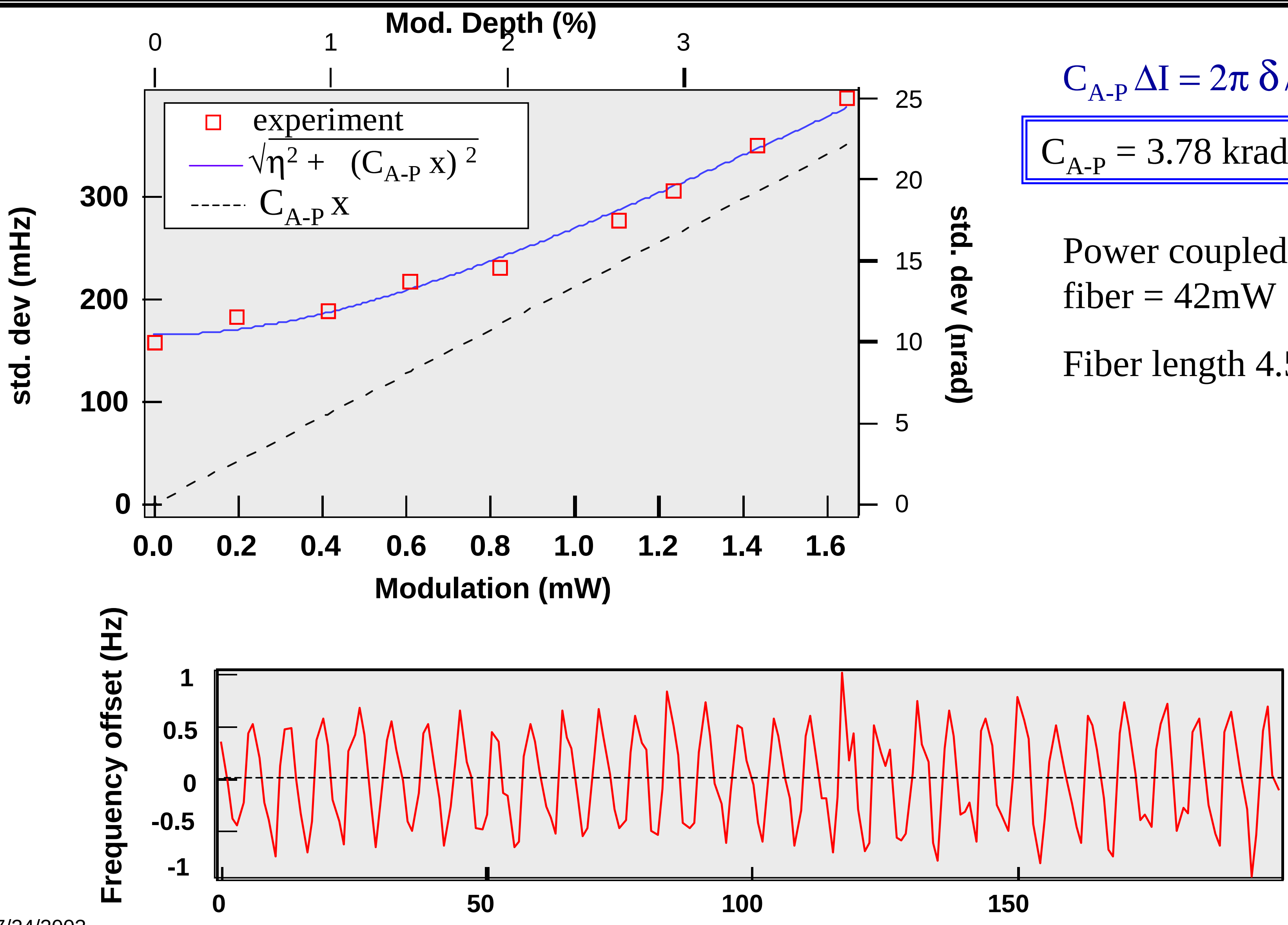
Amplitude to Phase Conversion Results



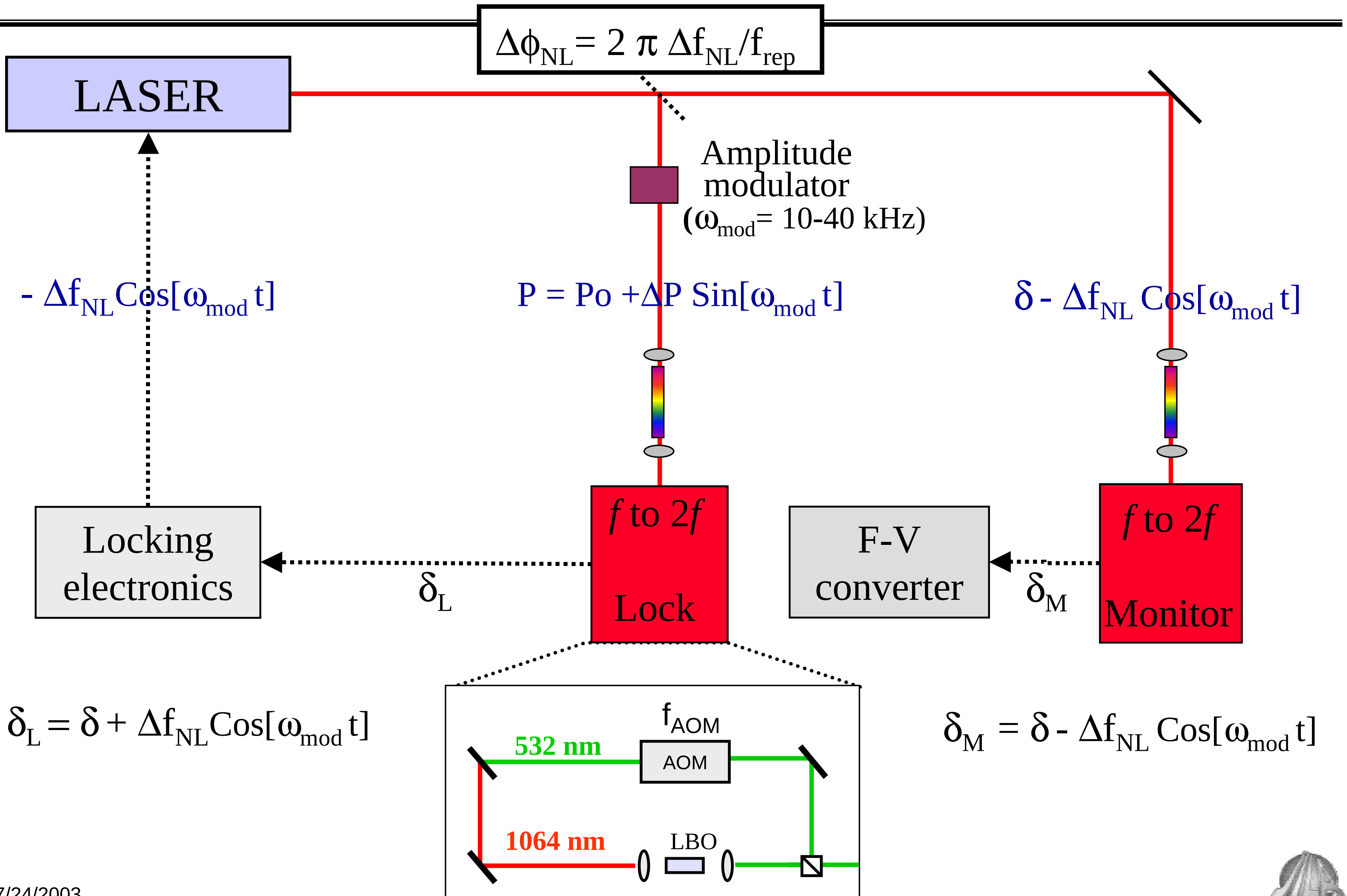
$$C_{A\text{-}P}\,\Delta I = 2\pi\,\delta / f_{mod}$$

$$\boxed{C_{A\text{-}P} = 3.78 \text{ krad /nJ}}$$

Power coupled into fiber = 42mW

Fiber length 4.5 cm

Dueling *f* to 2*f* 's: faster modulation

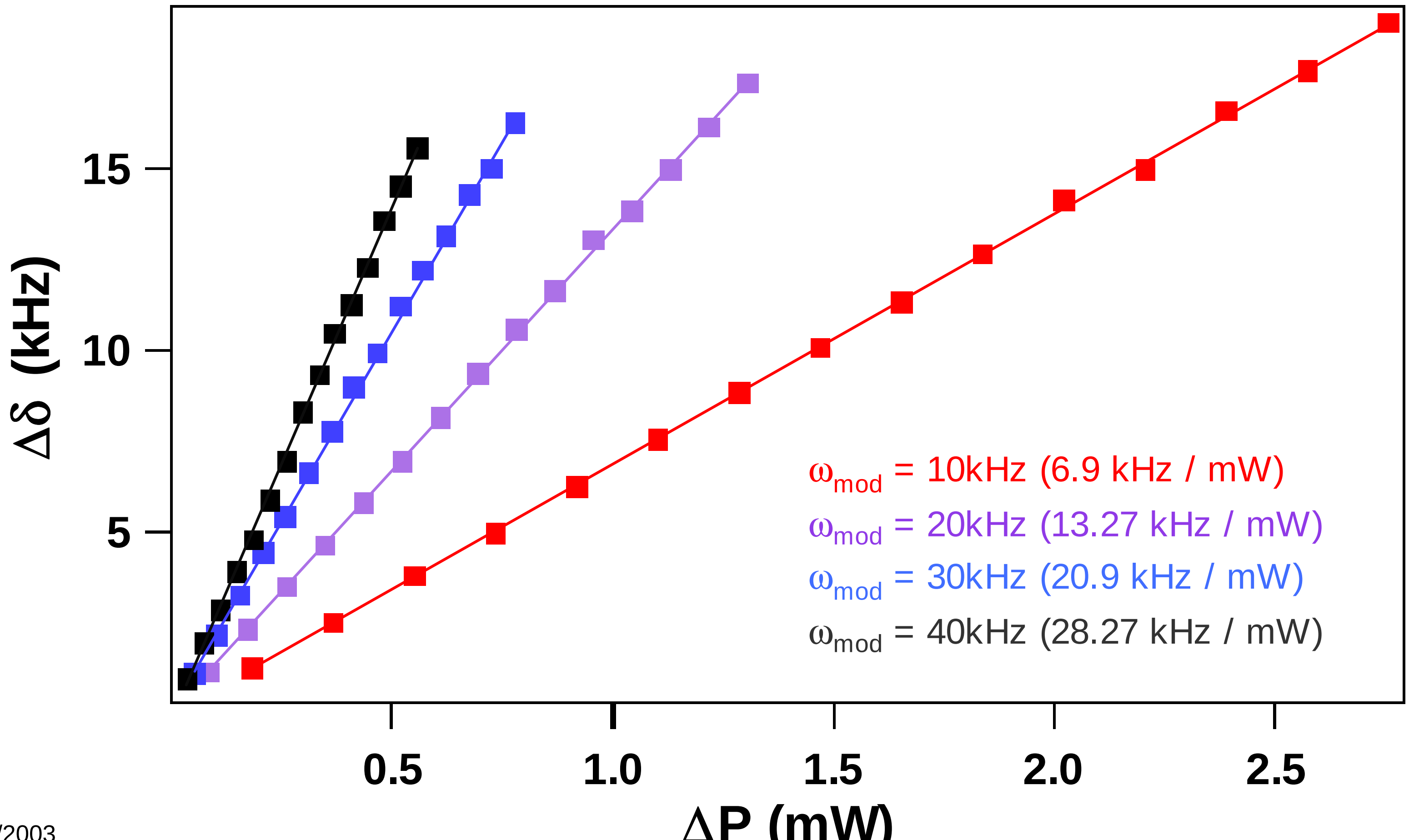


$$\delta_L = \delta + \Delta f_{NL} Cos[\omega_{mod}\, t]$$

$$\delta_M = \delta - \Delta f_{NL}\, Cos[\omega_{mod}\, t]$$

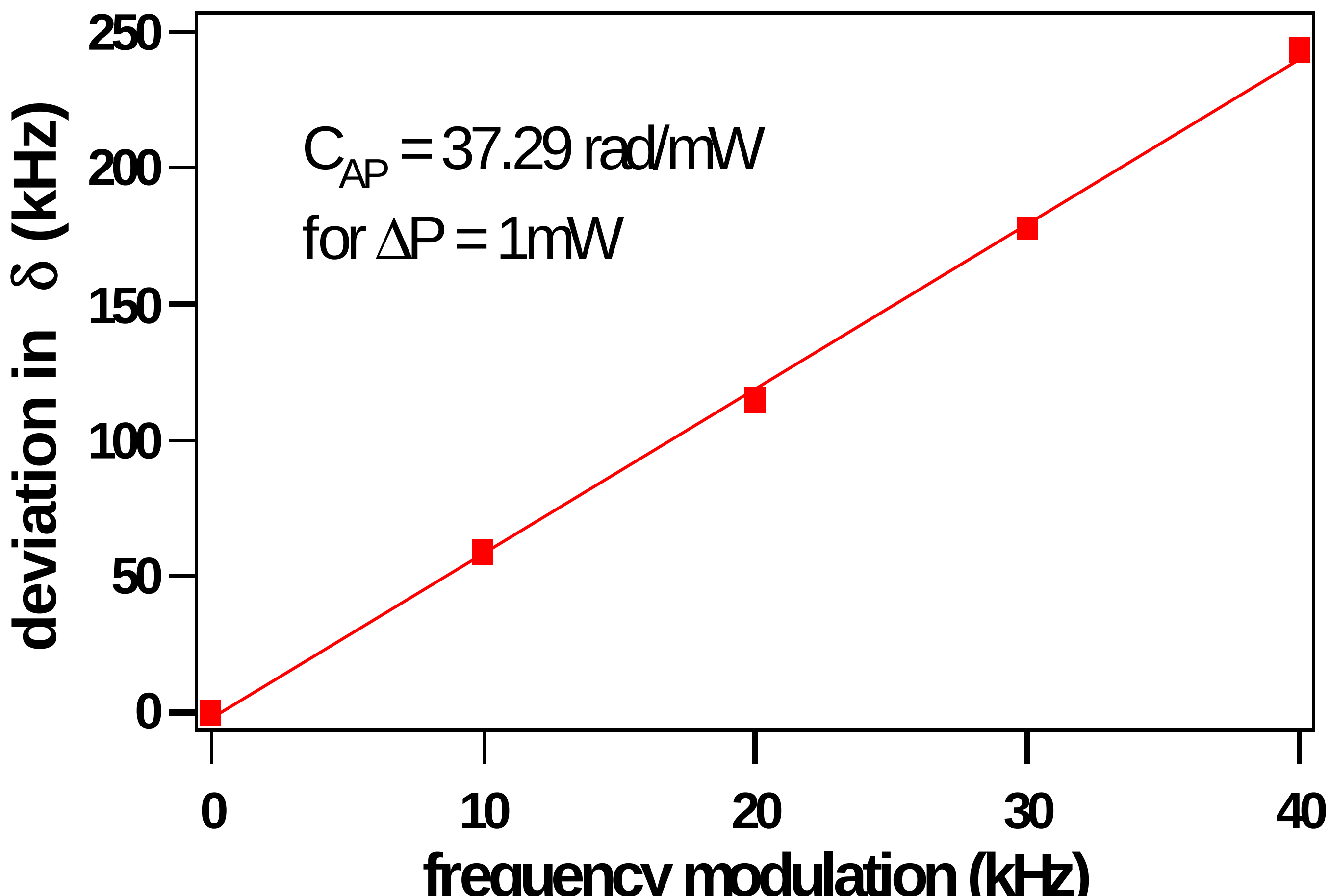
F-V Results

- Lower Background Noise
- Confirms modulation frequency dependence

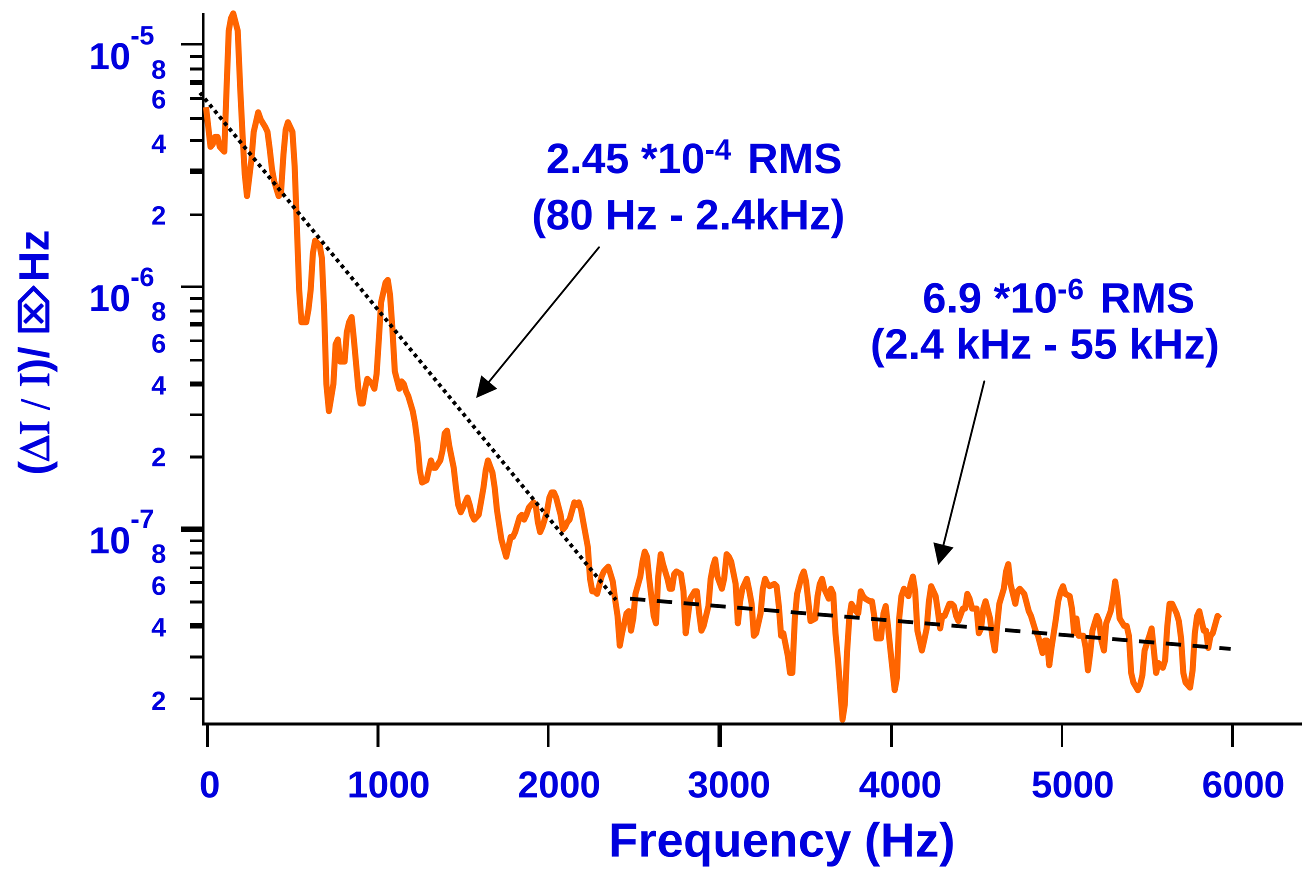


AM→PM Conversion Coefficient

- Same value as low frequency measurement

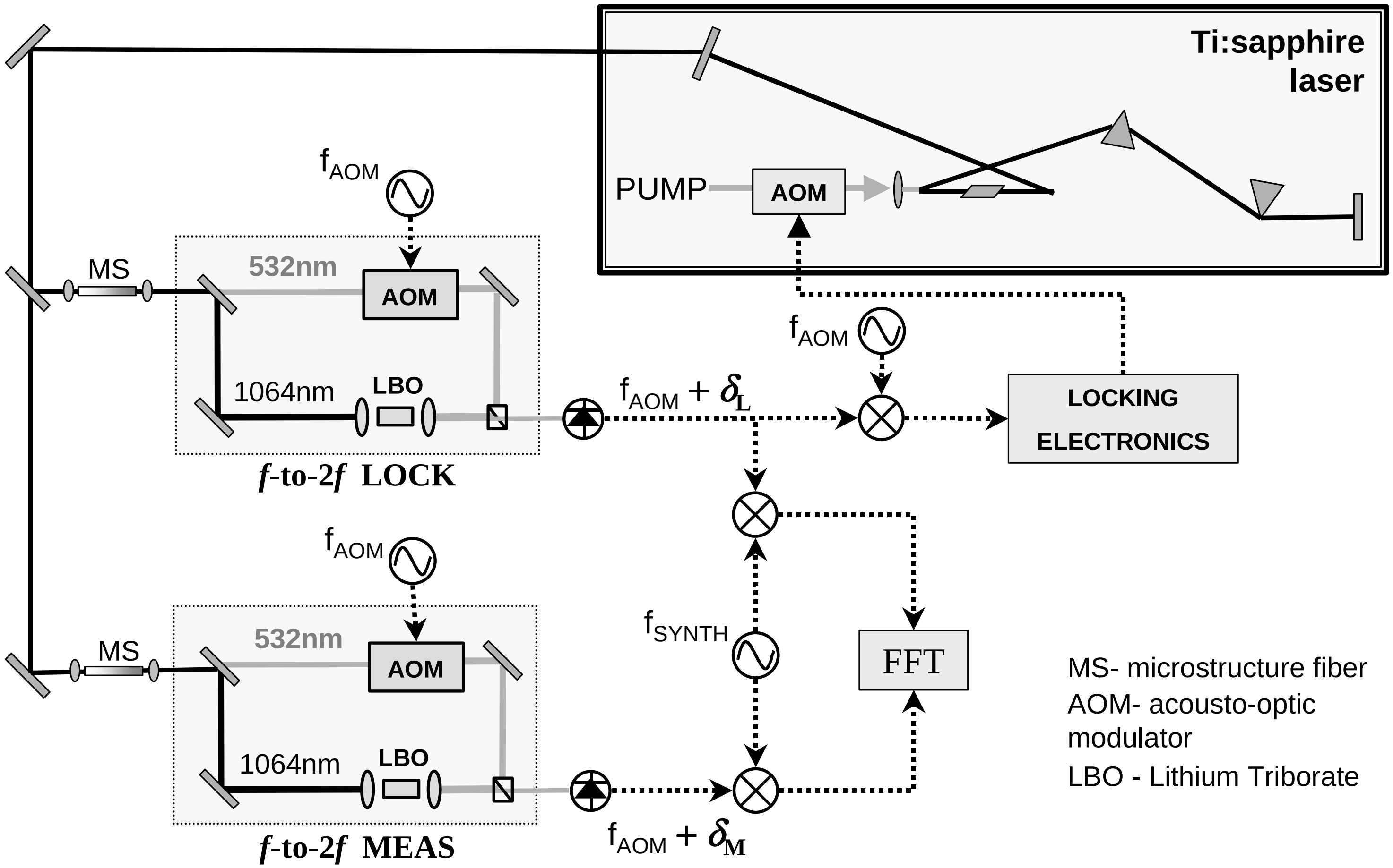


CE Phase noise due to fiber AM ► PM



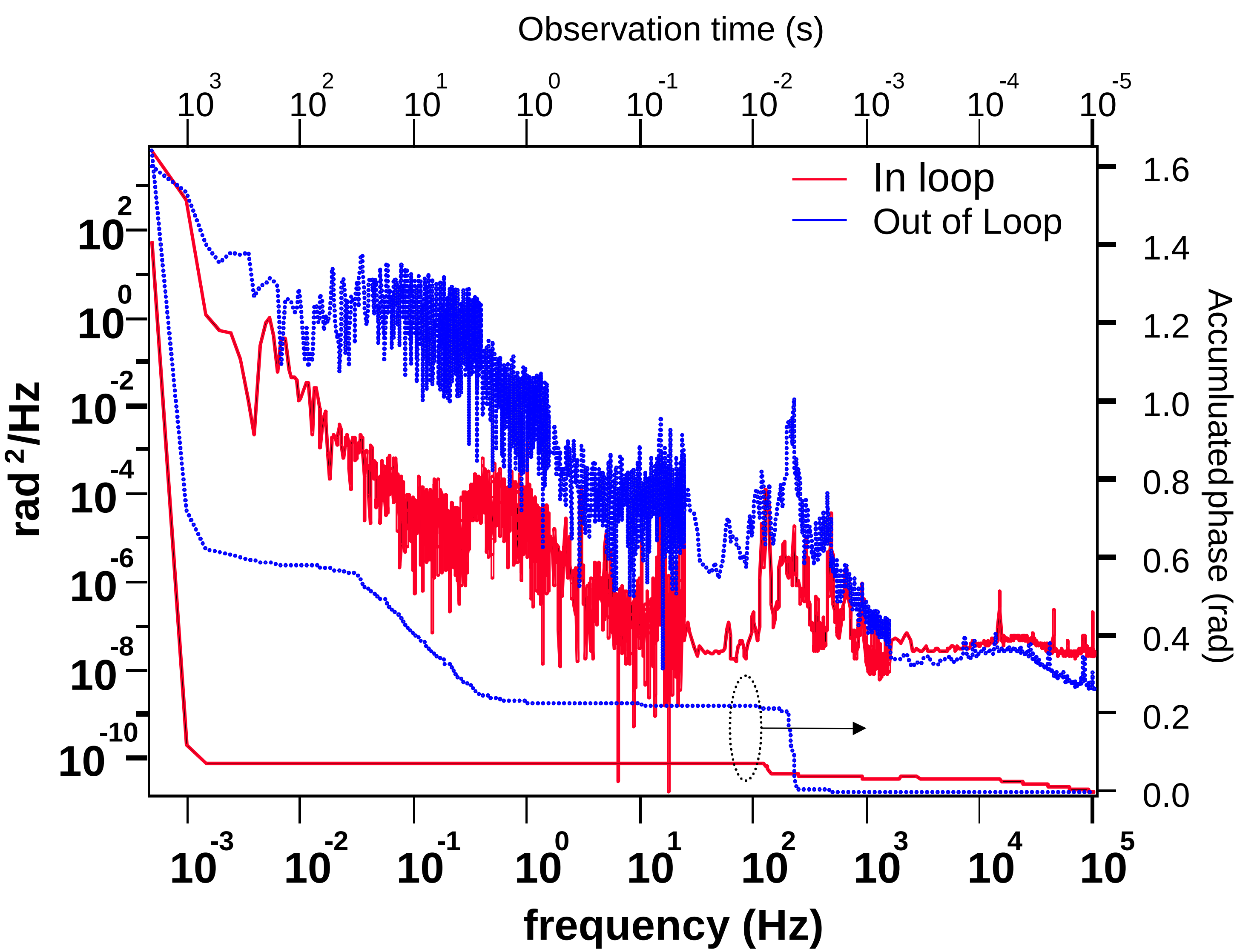
$$\Delta\phi_{NL\ RMS} = C_{AP}\,\Delta P_{RMS} = \sim 0.5\ \text{rad}\ \ (0.03\ \text{Hz} - 55\ \text{kHz})$$

Measurement of f_0 linewidth

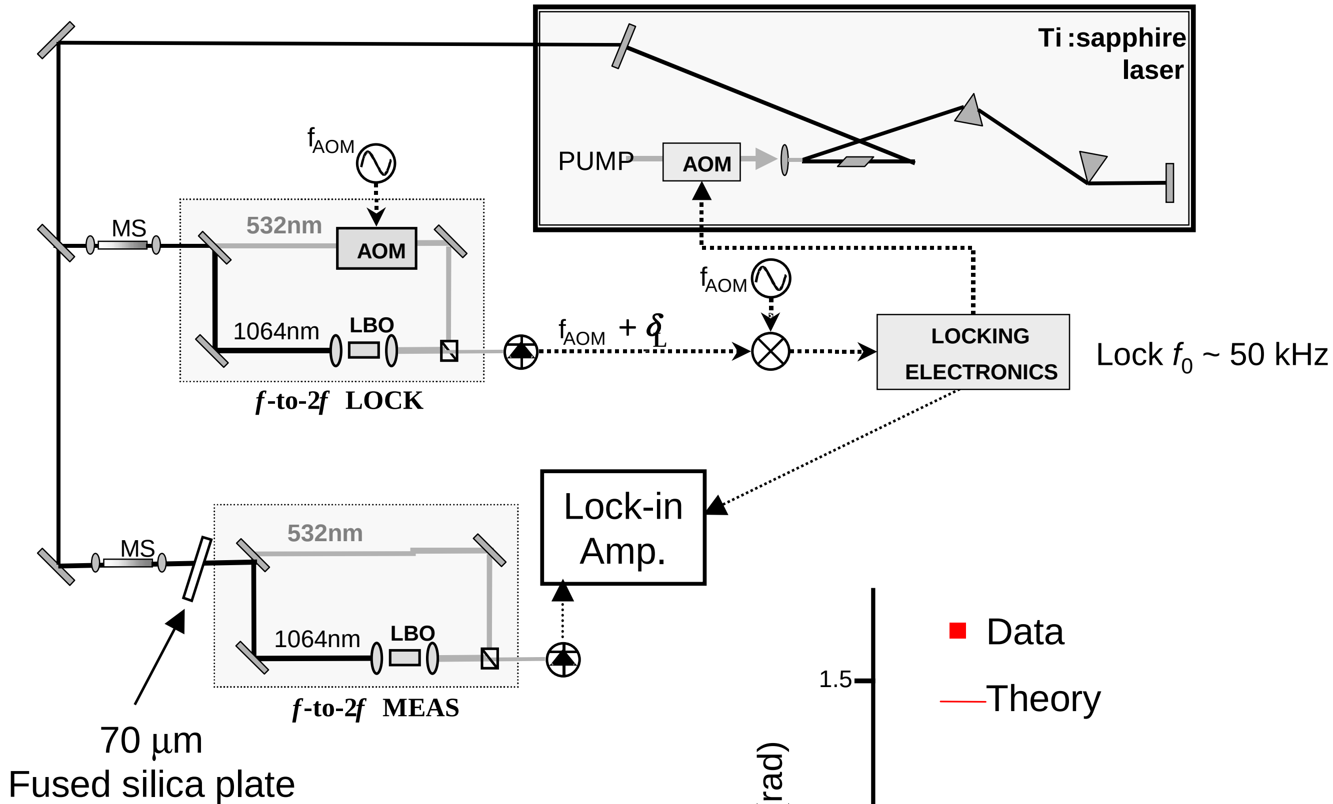


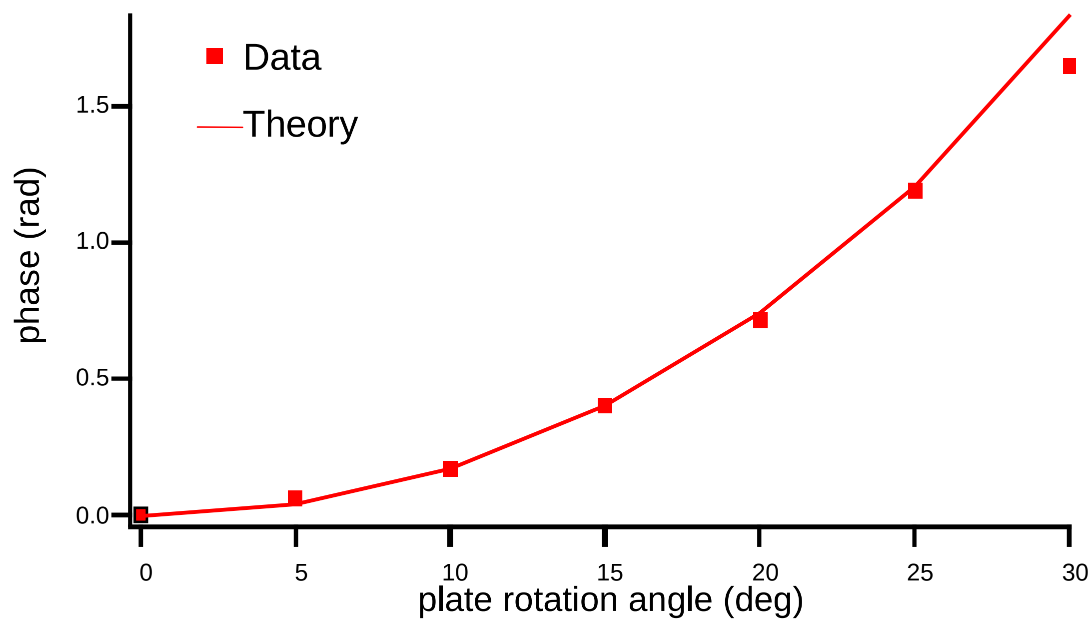
MS- microstructure fiber
AOM- acousto-optic modulator
LBO - Lithium Triborate

Phase noise spectrum



Direct Extra-cavity Measurement of $\Delta\phi_{CE}$



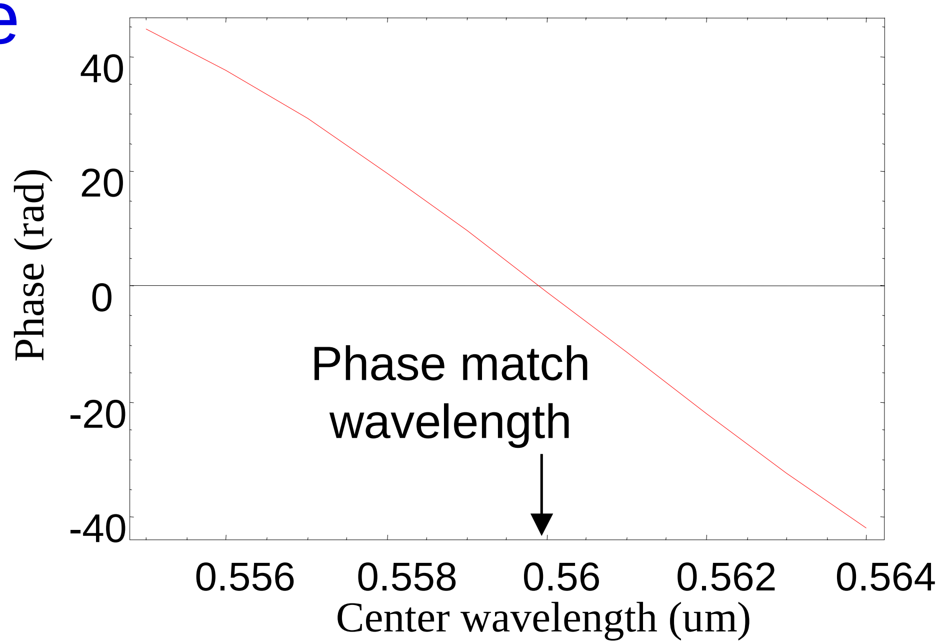


Measurement of "absolute" ϕ_{CE}

- Two arm interferometer adds arbitrary phase
  - Eliminate interferometer
  - Compress pulse
- Phase shifts in second harmonic crystal
  - None in exact phase matching (hard to achieve)
  - Short pulse inherently means sum frequency
- Quantum rather than optical interference
  - Semiconductor implementation: quantum interference control of injected currents

Phase errors in second harmonic

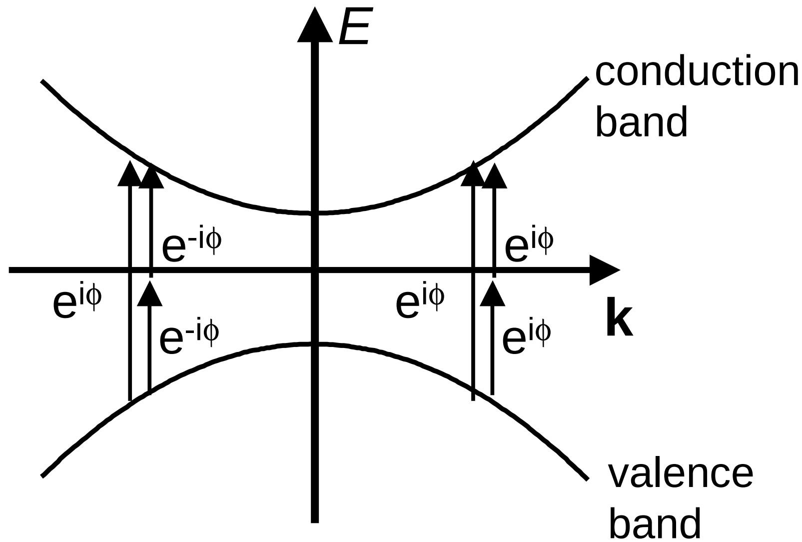
- Imperfect phase matching
- Detection at other than exact phase matching angle



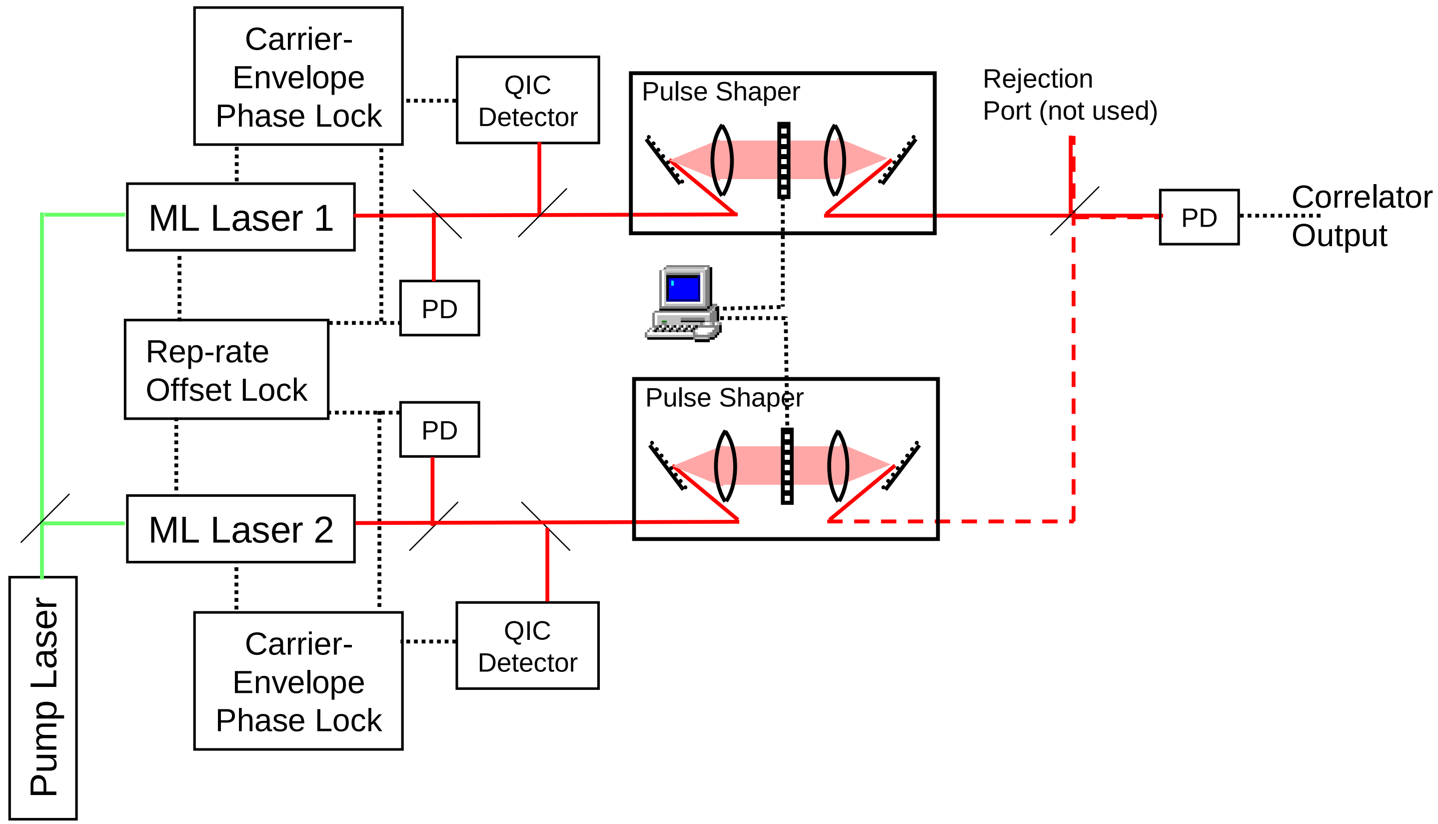
- Short pulse ⇨ range of wavelengths

Quantum Interference

- Interference between one-photon and two-photon absorption in LT-GaAs
- Yields current with direction that depends on ϕ_{CE}
- Calculations (Sipe & Bhat, U. Toronto) indicate detectable signal
- Thin (1 micron) active region



Prototype Correlator: Block Schematic



- ➢ Rep-rate offset lock to ML laser for fast scan
- ➢ Pulse shapers to generate waveforms from transform limited pulse

Summary

- Optical waveform synthesis based on control of the carrier-envelope phase is an interesting new approach to analog optical signal processing
- Achieved first milestone of improved carrier-envelope coherence
- Progress toward controlling the “absolute” carrier-envelope phase